

## Quantum beat spectroscopy of repulsive Bose polarons

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The physics of impurities in a bosonic quantum environment is a paradigmatic and challenging many-body problem. Here, this problem is investigated for impurities with strong repulsive interactions based on Ramsey interferometry in a quantum degenerate gas of  $^{39}\text{K}$  atoms. We observe revivals in the amplitude of the interferometric signal and identify them as beat signals between two coexisting quasiparticle branches, the attractive and repulsive polarons. The interferometric signal allows for an extraction of their energies for a wide range of interaction strengths, thus resolving outstanding discrepancies in earlier spectroscopic measurements. Furthermore, we identify several dynamical regimes in the formation of the repulsive Bose polaron. Our results improve the understanding of quantum impurities interacting strongly with a bosonic environment and show how short-lived nonequilibrium many-body states can be probed using quantum beat spectroscopy.

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As famously argued by Landau, a bare impurity particle smoothly evolves into a quasiparticle as the interaction with a surrounding quantum environment is adiabatically increased. Whereas the concept of quasiparticles was originally developed to understand the motion of electrons in solids [1], it now has a much broader scope and forms an incredibly successful platform for understanding strongly interacting quantum many-body systems [2–6].

Ultracold quantum gas experiments have in recent years improved our understanding of quasiparticles, as they allow one to perform Landau's gedanken experiment by tuning the interaction strength between an impurity atom and a surrounding quantum gas. This has led to the observation of the Fermi polaron [7–9], whose low-temperature properties are now well understood theoretically [10–12]. Furthermore, its nonequilibrium formation dynamics [13,14] and mediated interactions between two Fermi polarons [15] have been observed.

There is also strong experimental evidence for the Bose polaron with energies [16–19] and formation dynamics [20,21] in good quantitative agreement with theoretical predictions for attractive interactions. For repulsive interactions, the simplest picture [22] predicts two coexisting quasiparticles: a long-lived ground state attractive polaron and a higher-lying repulsive polaron as shown in Fig. 1. This is qualitatively supported by experiments but with severe discrepancies for the latter state [16,17,19]. A major difficulty in this respect is the inherent damping of the repulsive polaron, meaning that any reasonable spectroscopic probe pulse will easily be longer

than the lifetime of the state [21]. Moreover, there exists a plethora of theoretical predictions in this regime, which do not even agree on the number of expected states [22–34], and thus a consistent physical picture is only available in the weak-coupling regime [35,36].

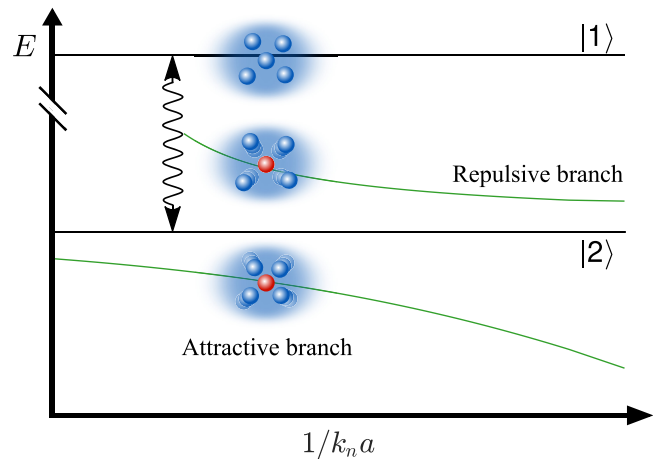


FIG. 1. Illustration of the employed Ramsey interferometry method and a simplified energy landscape of the system as a function of inverse interaction strength  $1/(k_n a)$ . A first radio-frequency (rf) pulse (black arrow) is applied to a Bose-Einstein condensate (BEC) in the initial electronic state  $|1\rangle$  (blue dots), which generates a small admixture in the impurity state  $|2\rangle$  (red dots). Due to its interaction with the background BEC this state is split in an attractive and a repulsive Bose polaron branch (green lines). A second rf pulse closes the interferometric sequence. The presence of two polaronic branches leads to the observation of a beat signal in the amplitude of the oscillatory interferometer output.

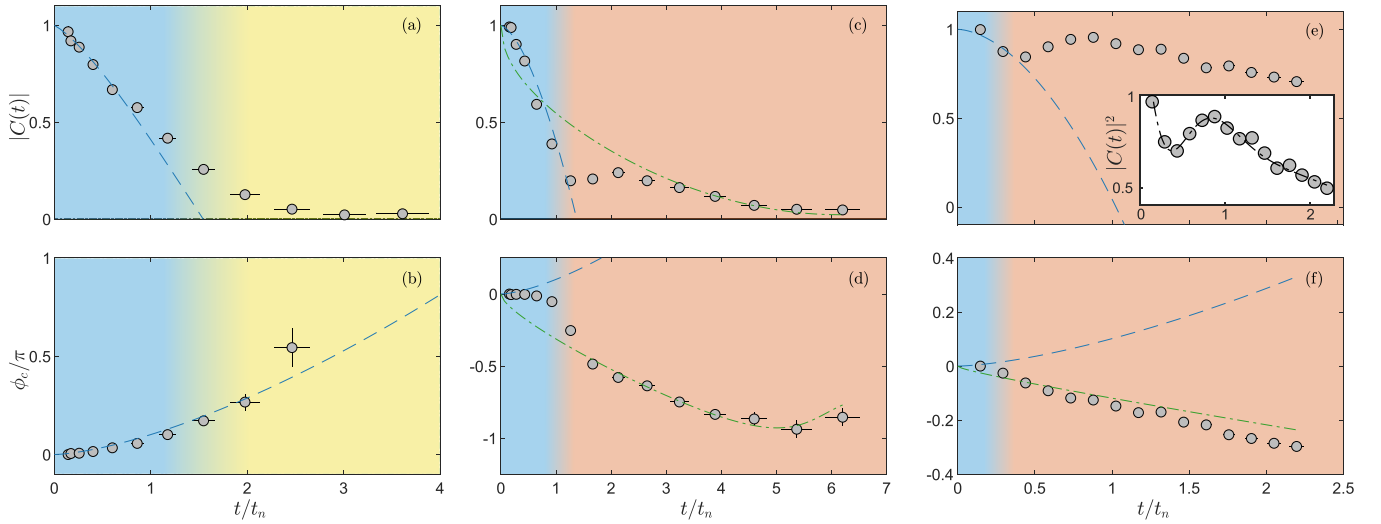


FIG. 2. Impurity dynamics at three characteristic interaction strengths. The coherence function is given for (a), (b) strong  $1/(k_n a) = 0.4$ , (c), (d) intermediate  $1/(k_n a) = 0.7$ , and (e), (f) weak  $1/(k_n a) = 1.5$  interaction strengths. For comparison, theoretical results for the unitarity-limited case in Eq. (1) (blue dashed line) and for weak two-body interaction Eq. (2) (green dashed-dotted line) are shown, without any free fitting parameters. Additional decoherence effects in the system due to three-body losses and the inhomogeneous density distribution, beyond Eqs. (1) and (2), are accounted for in the theoretical description [42].

In this Letter, we address this by probing the nonequilibrium dynamics of strongly interacting repulsive impurities in a Bose-Einstein condensate (BEC). The inherent difficulties due to decoherence effects and the short lifetime at strong interactions are mitigated by using Ramsey interferometry to perform *quantum beat spectroscopy*. This technique leads to a revival in the amplitude of the interferometric signal on top of a fast initial decay. The revival corresponds to a quantum beat between two coexisting quantum many-body states, which we identify as the attractive and repulsive polaron branches. Based on the initial decay, several nonequilibrium dynamical regimes are identified and explained theoretically. These results provide valuable information on impurity dynamics and the energy of the Bose polaron for repulsive interactions, addressing previously observed discrepancies for spectroscopic measurements [16,17,19]. Moreover, they showcase how techniques developed for understanding fast-decaying molecules [37] may be employed to understand damped quasiparticle states in quantum many-body systems.

The experiment is performed with  $^{39}\text{K}$  atoms in an optical dipole trap [38] and follows the same procedure as the investigations for attractive impurity-medium interactions [20]. The medium is a BEC in the  $|F = 1, m_F = -1\rangle \equiv |1\rangle$  hyperfine state, where  $F$  and  $m_F$  denote the total angular momentum quantum number and its projection, respectively. The  $|F = 1, m_F = 0\rangle \equiv |2\rangle$  hyperfine state constitutes the impurity state. The interaction between atoms in these two states is characterized by the scattering length  $a$ , which can be controlled with a magnetic Feshbach resonance at 113.8 G [39,40]. As a result, the interaction strength  $k_n a$  can be tuned at will from attractive,  $k_n a < 0$ , to repulsive,  $k_n a > 0$ , interactions, where  $k_n = (6\pi^2 n_B)^{1/3}$  is determined by the average density  $n_B$  of the BEC. The typical energy scale of the system is given by  $E_n = \hbar^2 k_n^2 / (2m)$ , with the mass  $m$  of  $^{39}\text{K}$ , which also provides the characteristic timescale  $t_n = \hbar / E_n$ .

The interferometric sequence is initiated by a radio-frequency (rf) pulse on resonance with the atomic transition between the  $|1\rangle$  and  $|2\rangle$  states [41], which produces a small 5% coherent admixture of the impurity state. Subsequently, the system evolves at the chosen interaction strength  $k_n a$  for a variable time  $t$  until a second rf pulse with a variable phase  $\phi$  between  $-\pi$  and  $\pi$  is applied.

We extract the signal from the loss of atoms due to three-body recombination, involving two condensate atoms and one impurity. The final number of atoms in the BEC has a sinusoidal dependence on the phase of the second rf pulse, which we parametrize as  $N(\phi) = N_0 - \mathcal{A} \cos(\phi - \phi_c)$ . The normalized coherence function is then given by  $C(t) = |\mathcal{A}(t)/\mathcal{A}(0)|e^{i\phi_c(t)}$ , which corresponds to the time-dependent Green's function of the impurity,  $G(t) = -iC(t) = -i\langle \Psi_{\text{BEC}} | \hat{c}(t) \hat{c}^\dagger(0) | \Psi_{\text{BEC}} \rangle$ , with the state of the BEC,  $|\Psi_{\text{BEC}}\rangle$ , and the creation operator for the impurity,  $\hat{c}^\dagger$  [14,20].

The observed coherence amplitude and phase evolution are shown in Fig. 2 for three interaction strengths on the repulsive side of the Feshbach resonance, displaying a number of striking features. The coherence amplitude shows a fast initial decay and a clear revival for intermediate and weak interaction strengths in Figs. 2(c) and 2(e). The phase initially increases and then reverses on a characteristic timescale, in Fig. 2(d), indicating the crossover between different dynamical regimes.

Importantly, the interferometric sequence populates two branches of many-body quantum states. The separate phase evolution in these branches due to their respective energies (see Fig. 1) leads to a distinctive quantum beat in the interferometric signal. This demonstrates the coherent coexistence of these many-body branches. In addition, these states decohere due to their strong interactions in combination with experimental decoherence effects. In the following, the results in Fig. 2 are discussed in detail.

Theoretically, the coherence function can be obtained from a Fourier transform of the spectral function. At short times, an expansion in orders of  $t/t_n$  yields

$$C(t) = 1 - (1 - i)k_{3/2}\left(\frac{t}{t_n}\right)^{3/2} - k_2\left(\frac{t}{t_n}\right)^2, \quad (1)$$

valid for times  $t \ll t_a = ma^2/\hbar$ . The second term is a consequence of unitarity-limited two-body interactions [43] with the universal constant  $k_{3/2} = 16/(9\pi^{3/2})$  [20,44]. The third term is an approximate second-order correction with  $k_2 = [Z_g(E_g/E_n)^2/2 - 4/(3\pi k_n|a|)]$ , which takes the attractive polaron with energy  $E_g$  and residue  $Z_g$ , as well as the high-frequency tail of the spectral function into account [21].

The measured coherence function in Figs. 2(a) and 2(b) for strong repulsive interactions  $1/(k_n a) = 0.4$  indeed agrees well with Eq. (1) at short times, as was also observed for attractive interactions [21]. We are thus able to quantitatively account for both the fast initial decay of the coherence amplitude as well as the initial positive phase evolution [45]. At intermediate interaction strengths of  $1/(k_n a) = 0.7$  in Figs. 2(c) and 2(d), similarly good agreement is obtained for short times, showing the presence of a universal regime also in this case. For weak interactions at  $1/(k_n a) = 1.5$ , shown in Figs. 2(e) and 2(f), the universal regime contains only a few data points, since  $t_a = 0.2t_n$ .

For intermediate to weak interactions, the attractive polaron branch lies close to the molecular state, with an energy given to first order by  $-\hbar^2/ma^2$ . Since the beat signal depends on the energy difference between the two branches it enters the dynamics on this timescale,  $t_a = ma^2/\hbar$ , after the system exits the unitarity-limited regime [42]. Thus the dynamical regime described by weak coupling dynamics is superimposed with quantum beats for  $t > t_a$ , which is qualitatively different from the case of attractive interactions,  $1/(k_n a) < 0$ , where no beats are observed.

The weak-coupling dynamics is to a good approximation described by

$$C(t) = e^{-iE_{\text{mf}}t/\hbar} e^{-(1+i)(t/t_w)^{1/2}}. \quad (2)$$

In this case the dynamics is governed by the mean-field phase evolution with  $E_{\text{mf}} = 4\pi\hbar^2 a n_B/m$ , and the coherence decays on an interaction strength-dependent timescale  $t_w = m/(32\pi\hbar n_B^2 a^4)$  [46], following a stretched-exponential form.

For longer times, the measured coherence amplitude and phase in Figs. 2(c) and 2(d) both agree well with this prediction, without, however, capturing the crossover from the initial dynamics or the beat signal. This is expected since Eq. (2) does not include the low-lying attractive polaron branch.

To examine the crossover in detail, the associated crossover time is extracted from the coherence phase [47]. We pinpoint the time at which the experimentally extracted coherence phase becomes closer to the result of Eq. (2) rather than Eq. (1). The crossover time is identified as the point in time between this and the previous data point. The extracted times are presented in Fig. 3, along with the expected dynamical regimes. The extracted crossover timescale is in very good agreement with the transition between unitarity-limited dynamics (blue region) and weak-coupling beating dynamics (orange region), set by the timescale  $t_a = ma^2/\hbar$  for

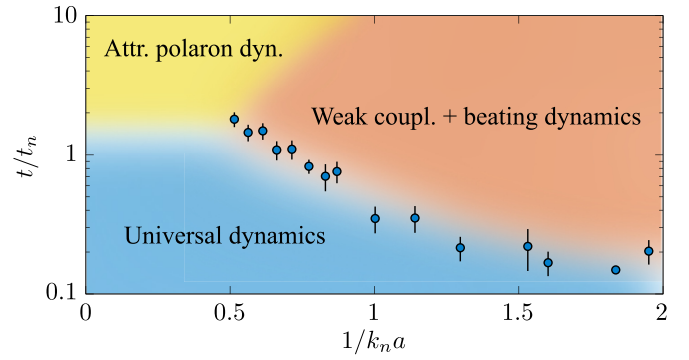


FIG. 3. Dynamics of impurity evolution for repulsive interactions. The characteristic dynamical regimes are indicated as a function of inverse interaction strength  $1/(k_n a)$  and evolution time  $t/t_n$ . The experimentally extracted crossover times (blue dots) indicate the transition from universal (blue region) to weak coupling and beating dynamics (orange region). For strong interactions and long times, the repulsive polaron decays, and the system is expected to transition into another dynamical regime (yellow region), in which the attractive polaron dominates the dynamics.

$1/(k_n a) > 0.5$ . This shows the existence of universal behavior at short times for all interaction strengths, extending the result in Ref. [20] to repulsive interactions.

For strong interactions, there is no regime where Eq. (2) applies. Instead, the short-time unitarity-limited dynamics given by Eq. (1) transitions directly to many-body dynamics, consistent with the case of strong attractive interactions [20]. Theoretically, it is expected that the repulsive polaron eventually decays, resulting in dynamics dominated by the attractive polaron, at which point the system enters a new dynamical regime (Fig. 3, yellow region). Experimentally, however, we did not observe a distinct signature of this crossover. This is expected since we theoretically observe that trap-induced density inhomogeneities significantly delay the crossover in the diagrammatic prediction [42].

We now analyze the quantum beat signal, clearly visible in Figs. 2(c) and 2(e), and present throughout the weak-coupling region in Fig. 3. Importantly, such a signal is not present for attractive interactions of  $1/(k_n a) < 0$ , but a similar feature was observed in interferometric investigations of the Fermi polaron [14].

The signal stems from the interference of coexisting repulsive and attractive branches, as demonstrated in the following. We apply a phenomenological model for the coherence function

$$C(t) = Z_g e^{-iE_g t/\hbar} + Z_r e^{-iE_r t/\hbar} e^{-\Gamma_r t/2}, \quad (3)$$

at intermediate- to weak-coupling strengths. This describes two states: a ground state at energy  $E_g$ , and a damped excited state with energy  $E_r > E_g$  and damping rate  $\Gamma_r$ , corresponding to the attractive and repulsive polarons with residues  $Z_g$  and  $Z_r$ , respectively.

This phenomenological model implies two main features of the coherence function in the weak-coupling regime. Since the repulsive branch is expected to have the largest residue, the relevant phase term is  $\varphi_c \approx -E_r t/\hbar$  and thus the phase evolution is expected to be linear in time. Moreover, the squared

amplitude of the coherence function includes oscillatory terms at a frequency  $\omega = (E_r - E_g)/\hbar$  which corresponds to the energy difference between the two branches associated with the quantum beat.

Inspired by this model, the experimental coherence amplitude squared and phase are fitted with the functions

$$|\mathcal{C}(t)|^2 = A e^{-t/\tau_1} \cos \omega t + B e^{-t/\tau_2}, \quad (4)$$

$$\varphi_c = A_\varphi - B_\varphi t. \quad (5)$$

This corresponds to the modulus squared of Eq. (3) with additional exponential decay terms to account for decoherence effects not included in the phenomenological model [42]. Since the phase evolution is governed by the energy of the repulsive branch rather than its population, it is robust to decoherence effects. The energy difference can be extracted from the fitting parameters as  $E_r - E_g = \hbar\omega$ . An example of the squared coherence amplitude fit is shown in the inset of Fig. 2(e). The observed revival is damped due to the inherent and experimental decoherence effects discussed above. This includes the decay of the repulsive branch, which attenuates the signal. However, for very weak interaction strengths, we observe more than one oscillation [42].

The fit to the phase evolution directly yields the energy of the repulsive branch,  $E_r = \hbar B_\varphi$ . This technique, however, can only be used when the phase evolution shows a consistent linear behavior [42]. This limits our analysis to  $1/(k_n a) > 0.85$ . To avoid the influence of the unitary regime, the linear fit is, additionally, restricted to  $t > t_a$ . Figure 4 (upper panel) shows the obtained energies for the repulsive branch for this range of interaction strengths. These energies lie consistently higher than the simple mean-field expectation and scatter around a Monte Carlo prediction [19]. Moreover, they lie systematically higher than our diagrammatic calculation based on the ladder approximation [42] and a variational truncated basis method [19]. The diagrammatic approach only qualitatively describes the dynamics at repulsive interactions, in contrast to attractive interactions, where it compares quantitatively well with experiments [20,21]. We attribute the discrepancy to the lacking ability of the diagrammatic approach to accurately describe the repulsive polaron branch.

The energy of the attractive branch is obtained by subtracting the extracted energy difference from the repulsive branch energy  $E_g = E_r - \hbar\omega$  as shown in Fig. 4 (lower panel). These energies agree with both the attractive polaron energy, obtained from diagrammatic calculations, and the molecular energy with an effective range given by the van der Waals length of our medium,  $R^* = 60a_0$  [16,42]. Experimentally, we cannot distinguish between these two results. However, the rf response of the molecular state is expected to be very small compared to the attractive polaron state, as has been previously measured for the Fermi polaron [8]. In particular, since the molecular state does not have a plane-wave component, we expect such a signal to scale with the density of generated impurities. This is indeed much weaker than the response from the attractive polaron state scaling with the density of the entire BEC. With this in mind, the above agreement confirms that the beat signal arises from interference between coherent coexisting quasiparticle branches. Furthermore, the linear fit

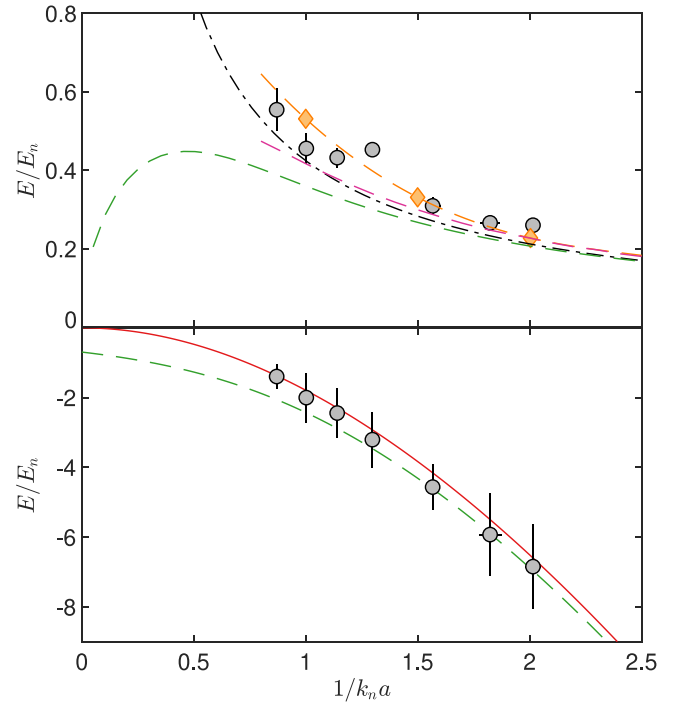


FIG. 4. Energies of the repulsive and attractive branches as a function of the inverse interaction strength. The measured energies are shown as gray points and the result of our diagrammatic calculation is indicated by green dashed lines [42]. Top panel: The repulsive branch energies lie clearly above the simple mean-field expectation (black dashed-dotted line) as well as a variational truncated basis method calculation (magenta dashed line) and is consistent with a quantum Monte Carlo prediction (yellow dashed line, diamonds) [19]. Bottom panel: The attractive branch energies are observed to agree with both the diagrammatic result and the molecular energy (red line).

to the phase yields a robust measurement of the repulsive branch energy within our phenomenological model.

In conclusion, we have performed Ramsey interferometry with strongly interacting impurities in a  $^{39}\text{K}$  BEC to investigate the bosonic impurity problem. The observed quantum beat signal demonstrates the coherent coexistence of a repulsive and an attractive quasiparticle branch within their lifetime, and no evidence has been found in support of additional spectral features [33]. A simple phenomenological model allowed for the simultaneous determination of the energy of these branches. The repulsive branch energies lie systematically above the simple mean-field expectation and are consistent with a quantum Monte Carlo prediction for all interaction strengths, significantly improving previous measurements [19]. Furthermore, the initial dynamics are observed to agree very well with the exact unitarity-limited behavior with the nonanalytical time dependence of  $t^{3/2}$  [20,44]. This confirms the general existence of universal behavior at short times for all interaction strengths.

At strong interactions of  $1/(k_n a) < 0.5$ , the dynamics follows the unitarity-limited behavior for long times. This, along with the quantitative discrepancy from the

diagrammatic calculations, calls for further theoretical analyses, especially at intermediate to strong repulsive interactions of  $0 < 1/(k_n a) < 1$ .

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