Non-equilibrium quantum dynamics and formation of the Bose polaron

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Advancing our understanding of non-equilibrium phenomena in quantum many-body systems remains one of the greatest challenges in physics. Here we report on the experimental observation of a paradigmatic many-body problem, namely the non-equilibrium dynamics of a quantum impurity immersed in a bosonic environment. We use an interferometric technique to prepare coherent superposition states of atoms in a Bose–Einstein condensate with a small impurity-state component, and monitor the evolution of such quantum superpositions into polaronic quasiparticles. These results offer a systematic picture of polaron formation from weak to strong impurity interactions. They reveal three distinct regimes of evolution with dynamical transitions that provide a link between few-body processes and many-body dynamics. Our measurements reveal universal dynamical behaviour in interacting many-body systems and demonstrate new pathways to study non-equilibrium quantum phenomena.

Landau’s quasiparticle theory is one of the most powerful concepts with which to understand many-body phenomena. Originally, the theory was developed to describe the interaction of an electron with phonons in a solid, leading to the formation of a quasiparticle. Nowadays it is widely used in many areas of physics and forms the basis for understanding fundamental phenomena such as transport processes, colossal magnetoresistance and superconductivity. Yet, the dynamical processes leading to the formation of quasiparticles has remained elusive in condensed-matter systems because of their high densities and, consequently, fast evolution times. Ultracold quantum gases offer a unique quantum simulation platform to address this problem, as they permit the controlled generation of impurity atoms inside a fermionic or bosonic quantum gas, where they perturb the surrounding medium to form quasiparticles called polarons. The study of Bose polarons is particularly important because the linear sound dispersion of the Bose–Einstein condensate (BEC) is analogous to that of phonons in a solid, leading to the formation of a quasiparticle.

The experiment was performed with Bose–Einstein condensates of 39K atoms in the \( |F = 1, m_F = -1\rangle \equiv |1\rangle \) hyperfine ground state, where \( F \) and \( m_F \) are the total angular momentum quantum number and its projection, respectively. The average condensate density \( n_0 \) sets the interaction independent energy scale \( E_n = \hbar^2 (6\pi^2 n_0)^{1/3}/2m \) of the system and the corresponding timescale \( t_n = h/E_n = 4.8 \mu s \). Here \( m \) is the mass of \( 39\text{K} \) and the subscript \( n \) indicates that the parameter is only density dependent in our experiments. For the controlled population of the impurity state we use a radiofrequency (RF) pulse to drive the transition to the \( |F = 1, m_F = 0\rangle \equiv |2\rangle \) state. The strength of the interaction is characterized by the dimensionless parameter \( 1/k_a a \), where \( a \) is the scattering length for collisions between the impurity and the condensate state, and \( k_a = (6\pi^2 n_0)^{1/3} \) is the characteristic wavenumber. We tune the scattering length \( a \) by applying a homogeneous magnetic field in the vicinity of a Feshbach resonance at 114 G (refs. 21,26,27), which does not affect the scattering length \( a_0 \) for collisions between the condensate atoms.

In this Letter, we make use of this capability to induce and trace the non-equilibrium dynamics of a quantum impurity from its initial creation to the eventual formation of the Bose polaron. We drive an atomic transition to coherently create a small population of an impurity state in a BEC. Its interaction with the surrounding BEC induces fast quantum evolution, which we probe by monitoring interferometrically the coherence between the initial state \( |1\rangle \) of the atoms and the impurity state \( |2\rangle \). This, in turn, yields a direct measurement of the time-dependent Green’s function of the impurity and thereby allows us to observe the non-equilibrium dynamics of the impurity that leads to the eventual formation of Bose polarons in a BEC.

Our measurements reveal distinct regimes of impurity evolution and thus yield a complete map of its dynamical behaviour, as shown in Fig. 1a. At short times, we observe a universal \( \sim t^{3/2} \) decay of the impurity coherence that does not depend on the coupling to the bosonic environment. This behaviour originates in high-energy two-body scattering with the surrounding condensate and governs the initial relaxation. It thus provides a clear experimental signature for such unitarity-limited processes. For weak interactions, an intermediate dynamical regime subsequently emerges. Here, low-energy collisions dominate the dynamical evolution, giving rise to a distinct \( \sim t^{1/2} \) decay of the impurity coherence. At longer times, we eventually observe pronounced deviations from such power-law behaviour, reflecting the emergence of many-body correlations that usher in the formation of the Bose polaron. The transitions between these dynamical regimes are shown in Fig. 1a. We observe remarkable agreement between theory and experiment for all impurity interaction strengths and evolution times, providing a quantitative understanding of the non-equilibrium dynamics of this quantum many-body system.

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amplitudes can be extracted for longer evolution times even at small signal-to-noise ratio, where the phase determination fails.

Based on these fits, we obtain the normalized coherence function

\[ C(t) = \frac{\langle A(t)/A(0) \rangle}{\langle |A(0)|^2 \rangle} \]  

(Supplementary Information). This, in turn, is directly proportional to the impurity Green's function

\[ G(t) = -iC(t) = -i\langle \psi_{\text{BEC}}(t)|\hat{c}(0)|\psi_{\text{BEC}} \rangle \]  

where \( |\psi_{\text{BEC}} \rangle \) describes the state of the BEC before the first RF pulse and \( \hat{c} \) is the operator that creates an impurity in the condensate. Consequently, \( C(t) \) is directly related to the spectral function of the impurity, which we compute using both a two-body and a many-body description to obtain \( C(t) \) throughout the impurity dynamics.

The initial dynamics can be calculated exactly for high energies, where it is determined by two-body physics\(^{10}\). A Fourier transform gives the corresponding exact short time dynamics, which has the limiting forms (Supplementary Information)

\[
C(t) = \begin{cases} 
1 - (1 - i) \frac{k}{2\pi} \left( \frac{t}{\tau_a} \right)^{3/2} & t \ll \tau_a \\
1 + \frac{k}{2\pi} \left( k_{\text{eff}} |a| \right)^2 - iE_{\text{int}} t/\hbar - (1 + i) \left( \frac{t}{\tau_a} \right)^{1/2} & t \gg \tau_a
\end{cases}
\]  

(1)

where \( E_{\text{int}} = 4\pi\hbar^2 n_{\text{BEC}} m \) is the mean field energy due to impurity state interactions with the BEC and \( \tau_a = ma^2/\hbar \). For times \( t \ll \tau_a \), equation (1) describes universal dynamics where the coherence of the impurity state decays with a power-law exponent of 3/2 on a timescale \( \tau_a \) independent of the (non-zero) interaction strength (Fig. 1a, blue area). This universal short time relaxation directly reflects the unitarity-limited scattering cross-section for short-range interactions, which does not depend on \( a \) for collision energies greater than \( h/ma^2 \). Hence, the time \( \tau_a \) marks the crossover (Fig. 1a, blue to green transition) to a regime where the dynamics is governed by the mean field phase evolution \( E_{\text{int}} t/\hbar \), and the coherence decays with a power-law exponent 1/2 on a timescale \( \tau_a \) independent of the (non-zero) interaction strength (Fig. 1a, green area). This behaviour arises from weak two-body collisions with a constant cross-section \(-a^2\) (ref. 10).

An intuitive understanding of the power laws in equation (1) can be gained from the cross-section \( \sigma(\kappa) = 4\pi\kappa/(1 + (ka)^2) \) assuming that the rate of decoherence is given by the collision rate \( \bar{C}(t) \approx -n_{\text{BEC}} \bar{v} \). At a time \( t \) after initializing the system, decoherence is caused by coupling to states with \( E \approx \hbar t/\tau_a \) setting the wavenumber \( k \approx \sqrt{\hbar/\tau_a} \) and the collisional velocity \( v \approx \sqrt{\hbar/\tau_a} \). For \( t \ll \tau_a \), the cross-section is unitarity-limited, \( \sigma \approx 1/\kappa \approx \hbar t/ma^2 \) and integrating the decoherence rate yields the universal limit \( C(t) \approx (t/\tau_a)^{-3/2} \). At longer times \( t \gg \tau_a \), the cross-section is determined by low-energy collisions \( \sigma \sim a^2 \) and integrating gives \( C(t) \approx (t/\tau_a)^{-1/2} \) in accordance with the weak coupling limit (Supplementary Information).

At later times, interactions between multiple particles lead to pronounced deviations from the two-body prediction given by equation (1) and the system enters a regime of many-body dynamics (Fig. 1a, orange area). We describe this many-body dynamics using a diagrammatic theory (Supplementary Information), which has previously been applied to the equilibrium physics of Bose polaronic\(^{10,11}\). Because our many-body theory contains the dominant two-body processes, it moreover recovers the two-body prediction of equation (1) for short times. For weak interactions, deviations from two-body weak coupling \( t^{1/2} \) dynamics occur at times \( \sim h/E_{\text{int}} \) (Fig. 1a, green to orange transition). However, for large interaction strengths where \( E_{\text{int}} \gg h^2/ma^2 \) and consequently \( 1/k_{\text{eff}} a < (2\pi)^{3/2} \), the many-body dynamics emerges directly from the initial universal regime at times \( \sim 1/\tau_a \) (Fig. 1, blue to orange transition). We emphasize that these changes in dynamical behaviour correspond to smooth temporal crossovers, as indicated by the blurred boundaries in Fig. 1a.
Figure 2 | Impurity dynamics at weak interaction strength. a. The interference signal recorded at different evolution times as a function of the probe pulse phase $\varphi$ for an interaction strength $1/k_0 a = -2$. Sinusoidal fits are shown as solid lines and the obtained amplitude and phase are indicated using grey lines and open circles, respectively. b, Coherence amplitude $|C(t)|$. The impurity state decoheres due to interactions with the condensate. c. Phase of the coherence, $\varphi(t)$. The impurity phase increases as the state rotates on the Bloch sphere, which at weak interaction strength is primarily due to the impurity state mean field interactions $\mathcal{E}_m$. The dashed blue line shows the two-body universal $t^{1/2}$ and the dash-dotted green line shows the weak coupling $t^{3/2}$ dynamics according to equation (1). The solid orange line provides the diagrammatic description and the coloured areas illustrate the theoretically predicted dynamical regimes from Fig. 1a. The error bars are $1\sigma$ confidence intervals of the fitted values.

Figure 3 | Impurity dynamics at intermediate interaction strength. a,b. Coherence amplitude (a) and phase evolution (b) for $1/k_0 a = -0.77$. The two-body universal $t^{1/2}$ prediction of equation (1) is shown as a dashed blue line. The solid orange line is the diagrammatic prediction and the coloured areas illustrate the theoretically predicted dynamical regimes from Fig. 1a. The error bars are $1\sigma$ confidence intervals of the fitted values.

For longer evolution times, we observe pronounced deviations from equation (1), signalling the onset of many-body correlations due to the strong interaction between the impurity state and the condensate. This behaviour is captured by the diagrammatic prediction, which yields an excellent description of the non-equilibrium dynamics of impurities in the regime of strong interactions and thus demonstrates the many-body nature of the long-time impurity evolution in our experiments. In particular, the data reveal a clear crossover between the initial two-body $t^{1/2}$ dynamics and a slower many-body decay at a transition time, as indicated by a white data point in Fig. 1a.
in a time-resolved manner. Elucidating the dynamics of induced quasiparticle interactions could prove essential, as strong retardation and relaxation effects3,35 may render such bipolarons inaccessible to common spectroscopic methods33,34.

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Fig. 4 | Impurity dynamics at unitarity. a, Coherence amplitude and phase evolution (inset). The fast initial decay of the coherence amplitude is in good agreement with the unitary two-body prediction of equation (1), shown as a dashed blue line. At longer times, many-body physics dominates the decay, which is well described by a diagrammatic description that accounts for many-body effects, shown as a solid orange line. b, Instantaneous energy obtained from the time derivative of the observed phase. The measured energies agree with the result of diagrammatic theory, shown as a solid orange line, and approach the expected equilibrium energy of the Bose polaron E_p, marked with a dashed line. The coloured areas illustrate the theoretically predicted dynamical regimes from Fig. 1a and the error bars are τr confidence intervals of the fitted values.

Moreover, the measured phase evolution allows us to track the instantaneous energy of the impurity. Because the phase evolution \( \phi(t) \rightarrow \phi_t / \hbar \) for long times is governed by the polaron energy \( E_p \), we obtain the instantaneous energy from \( E(t) = -\hbar \phi_t / \Delta \). As shown in Fig. 4b, the observed impurity energy approaches the expected equilibrium polaron energy. Therefore, our measurements directly display the dynamical emergence of the Bose polaron in the regime of strong interactions.

Our experiment covers all relevant timescales of quasiparticle formation and thus opens up new pathways to study non-equilibrium phenomena in strongly interacting quantum many-body systems. The demonstrated technique will enable investigations of bosonic analogues of Anderson’s orthogonality catastrophe35,36 and transport processes35,36 via time-domain measurements. Similar measurements at repulsive impurity interactions will be able to explore the predicted formation of multi-phonon bound states. Experiments with higher impurity concentrations will permit the investigation of effective polaron interactions35. Such mediated interactions are believed to play a vital role for transport properties of condensed-matter systems35. Ultimately, this may enable the observation of strongly bound bosonic bipolarons35 and their formation in a time-resolved manner. Elucidating the dynamics of induced quasiparticle interactions could prove essential, as strong retardation and relaxation effects3,35 may render such bipolarons inaccessible to common spectroscopic methods35,36.
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Methods
Experimental preparation. To study the impurity dynamics, a Bose–Einstein condensate of $^{87}\text{K}$ atoms in the $|F = 1, m_F = -1\rangle$ state was prepared in an optical dipole potential. The evaporation was performed near a Feshbach resonance at 33.6 G before ramping the magnetic field to a desired value close to the interstate Feshbach resonance at 113.8 G. The cloud temperature was kept constant at 50 nK throughout the measurements and the mean geometrical trap frequency was $2\pi \times 65$ Hz, ensuring an average condensate density of $n_B = 0.7 \times 10^{14}$ cm$^{-3}$.

Decoherence. Three additional experimental decoherence processes are included in the theoretical description of the coherence. To account for processes due to trap inhomogeneity, the coherence amplitude and phase were integrated over the cloud density. The effects of finite lifetime were included by multiplying the theoretical coherence amplitude with an exponential function based on an independently measured loss rate $\Gamma_{\text{loss}}$. The magnetic field noise was included similarly by multiplying the theoretical coherence amplitude with a decay due to shot-to-shot fluctuations, which was measured independently (Supplementary Information).

Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability
The code that supports the findings of this study is available from the corresponding author upon reasonable request.

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Author contributions
M.G.S., T.G.S., N.B.J. and J.J.A. designed and carried out the experiment. M.G.S. performed the data analysis. K.K.N., A.C.-G., T.P. and G.M.B. provided the theoretical predictions. All authors contributed to writing the manuscript.

Competing interests
The authors declare no competing interests.

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