Ultracold Fermi gases with tunable interactions provide a test bed for exploring the many-body physics of strongly interacting quantum systems. Over the past decade, experiments have investigated many intriguing phenomena, and precise measurements of ground-state properties have provided benchmarks for the development of theoretical descriptions. Metastable states in Fermi gases with strong repulsive interactions represent an exciting area of development. The realization of such systems is challenging, but the strong repulsive interaction in an atomic quantum gas implies the existence of a weakly bound molecular state, which makes the system intrinsically unstable against decay. Here we use radio-frequency spectroscopy to measure the complete excitation spectrum of fermionic $^{40}$K impurities resonantly interacting with a Fermi sea of $^6$Li atoms. In particular, we show that a well-defined quasiparticle exists for strongly repulsive interactions. We measure the energy and the lifetime of this ‘repulsive polaron’ and probe its coherence properties by measuring the quasiparticle residue. The results are well described by a theoretical approach that takes into account the finite effective range of the interaction in our system. We find that when the effective range is of the order of the interparticle spacing, there is a substantial increase in the lifetime of the quasiparticles. The existence of such a long-lived, metastable many-body state offers intriguing prospects for the creation of exotic quantum phases in ultracold, repulsively interacting Fermi gases.

Landau’s theory of Fermi liquids, and the underlying concept of quasiparticles, is central to our understanding of interacting Fermi systems over a wide range of energy scales, including liquid helium-3, electrons in metals, atomic nuclei and quark–gluon plasma. In the field of ultracold Fermi gases, the normal (non-superfluid) phase of a strongly interacting system can be interpreted in terms of a Fermi liquid. In the population-imbalanced case, quasiparticles known as Fermi polarons are the essential building blocks and have been studied in detail experimentally for attractive interactions. Recent theoretical work has suggested a novel quasiparticle associated with repulsive interactions. The properties of this repulsive polaron are of fundamental importance to the physics of repulsive many-body states. A crucial question for the feasibility of future experiments is the stability against decay into molecular excitations. Indeed, whenever a strongly repulsive interaction is realized by means of a strongly interacting regime. The inset illustrates our radio-frequency (RF) spectroscopic scheme whereby the impurity is transferred from a non-interacting spin state, $|0\rangle$, to the interacting state, $|1\rangle$.
polaron, which has recently received a great deal of attention theoretically,\textsuperscript{4,15,23–25} as well as experimentally.\textsuperscript{6,17,26} This polaronic branch remains the ground state of the system until a critical interaction strength is reached, where the system energetically prefers to form a bosonic $^4\text{He}$ molecule by binding the $^4\text{He}$ impurity to a $^6\text{Li}$ atom from the Fermi sea.\textsuperscript{23,25,27} The MHC arises from the fact that an atom with an energy between 0 and $\epsilon_b$ can be removed from the Fermi sea to form the molecule. This continuum thus exists in an energy range between $E_m$ and $E_m - \epsilon_b$ (Fig. 1, dashed lines), where $E_m$ is the energy of a dressed molecule including the binding energy of a bare molecule in vacuum and a positive interaction shift. The attractive polaron can decay into a molecular excitation if this channel opens up energetically ($E_- \geq E_m - \epsilon_b$).

The upper branch (Fig. 1, red line) corresponds to the repulsive polaron,\textsuperscript{9,12,13} with an energy $E_+ > 0$. Approaching the FR from the $a > 0$ side, $E_+$ gradually increases and reaches a sizeable fraction of $\epsilon_b$. However, the polaronic state becomes increasingly unstable as it decays to the lower-lying states (attractive polaron and MHC). Close to the FR centre, the repulsive polaronic state becomes ill-defined as the decay rate approaches $E_+/\hbar$.

To investigate the excitation spectrum of the impurities, we use radio-frequency spectroscopy.\textsuperscript{28–30} We initially prepare the $^4\text{He}$ atoms in a non-interacting spin state, $|0\rangle = |F = 9/2, m_F = -7/2\rangle$ and then, with a variable frequency, $\nu_{rf}$, drive radio-frequency transitions into the resonantly interacting state $|1\rangle = |F = 9/2, m_F = -5/2\rangle$. Our signal is the fraction of atoms transferred, measured as a function of the radio-frequency detuning, $\Delta = \nu_{rf} - \nu_0$, with respect to the unperturbed transition frequency, $\nu_0$, between the two spin states. This excitation scheme provides access to the full energy spectrum of the system. In particular, it allows us to probe the metastable repulsive polaron as well as all states in the MHC. We furthermore take advantage of the coherence of the excitation process by driving Rabi oscillations. This is an important practical advantage, because it allows very fast and efficient transfer of population into a short-lived quasiparticle state by application of $\pi$-pulses. Moreover, we find that measurements of the Rabi frequency directly reveal quasiparticle properties (see below).

In Fig. 2, we show false-colour plots of our signal as detected for different values of the detuning parameter, $\Delta = \hbar(\nu_{rf} - \nu_0)$, and for variable interaction strength, $1/\kappa_{qa}$. Figure 2a displays a set of measurements that we optimized for the signal strength and spectral resolution of the polaronic excitations by using moderate radio-frequency power. The two insets show the polaron peaks on top of a background due to additional excitations in the Fermi sea (Supplementary Information). The spectrum in Fig. 2b was optimized for detection of the molecular excitations. Here we had to use a much higher radio-frequency power (greater than that in Fig. 2a by a factor of 100) because of the reduced Franck–Condon wavefunction overlap. For the polaronic branches, the high radio-frequency power leads to highly nonlinear saturation behaviour.

Our data show both polaronic branches, and the measured energies of the branches are in excellent agreement with theory. The attractive polaron is found to disappear in the strongly interacting regime. This behaviour, which is different from that observed in $^6\text{Li}$ spin mixtures,\textsuperscript{16} is consistent with the crossing of $E_-$ and $E_m - \epsilon_b$ at $1/\kappa_{qa} = 0.6$ as we expect for our system. By contrast, the repulsive polaron extends far into the strongly interacting regime. The spectrum has a sharp peak that fades out near $1/\kappa_{qa} = -0.3$ (Supplementary Information). The low radio-frequency power produces only a weak MHC signal (Fig. 2a), whereas for high radio-frequency power the MHC signal is strong (Fig. 2b). For weaker interactions on the $a > 0$ side of the FR ($1/\kappa_{qa} < -1$), the molecular signal decreases because of the reduced Franck–Condon overlap. Outside the strongly interacting regime, the situation corresponds to the radio-frequency association of bare molecules (Supplementary Information).

To investigate the decay of the repulsive branch, we apply a radio-frequency pulse sequence to convert repulsive polaron in state $|1\rangle$ back into non-interacting impurities in state $|0\rangle$ after a variable hold time (Methods). This back-conversion depends sensitively on the radio-frequency resonance condition and thus allows us to discriminate $^4\text{He}$ atoms in the polaronic state from those forming molecules. In Fig. 3, we present the experimental results. The inset shows three sample curves taken for different values of the interaction parameter. The main panel displays the values extracted for the decay rate, $\Gamma$, from the decay curves using exponential fits. The data reveal a pronounced increase in decay as the FR centre is approached, which is in good agreement with theoretical model calculations (Fig. 3, solid lines; Supplementary Information). The decay populates the MHC and may occur in a two-step process whereby the repulsive polaron decays via a two-body process into an attractive polaron (Fig. 3, blue line) that in turn decays into a molecular excitation. Alternatively, the repulsive polaron may decay directly into the MHC in a three-body process (Fig. 3, red line). Very close to the FR centre, for $1/\kappa_{qa} = -0.25$, we find that $\hbar/\Gamma_{\epsilon_b} = 0.01$, which corresponds to a 1/e lifetime of about 400 $\mu$s. By comparing this decay rate with the corresponding energy shift, $E_+ = 0.30\epsilon_b$, we obtain $\hbar/\Gamma_{E_+} \approx 0.03 < 1$, which demonstrates that the repulsive polaron exists as a well-resolved, metastable quasiparticle even deep in the strongly interacting regime.
The lifetime observed for the repulsive branch is remarkably long, when compared with findings in recent experiments on $^6$Li spin mixtures\textsuperscript{11}. The latter mass-balanced system features a broad FR with a negligible effective range ($R^* \rightarrow 0$). Our theoretical approach allows us to give a general answer to the question of how mass imbalance and the width of the FR influence the lifetime. We find that the mass imbalance has only a minor role\textsuperscript{12} and that the dominant effect results from the finite effective range. In the strongly repulsive regime, our system allows us to obtain the same amount of repulsive interaction energy as would a hypothetical system with a broad FR ($R^* \rightarrow 0$), but with an almost ten-fold increased lifetime (Supplementary Information).

Apart from energy and lifetime, the polaron is characterized by its effective mass, $m^*$, and its quasiparticle residue, $Z$ ($0 \leq Z \leq 1$). The difference between $m^*$ and the bare mass\textsuperscript{12} does not produce any significant features in our radio-frequency spectra. The residue quantifies how much of the non-interacting particle is contained in the polaron’s wavefunction, which can be written as $\sqrt{Z}|1\rangle$ plus terms describing excitations in the Fermi sea. The pre-factor $\sqrt{Z}$ directly manifests itself in the Rabi frequency, $\Omega$, that describes the coherent radio-frequency coupling between the non-interacting state and the polaronic state (Supplementary Information).

In Fig. 4, we show the experimental data on Rabi oscillations for variable interaction strength. The sample curves in Fig. 4a demonstrate both the interaction-induced change in the frequency and a damping effect. We apply a simple harmonic oscillator model (including a small increasing background) to analyse the curves, which yields the damping rate, $\gamma$, and the frequency, $\Omega$. The damping strongly increases close to the FR centre, but does not show any significant dependence on the unperturbed Rabi frequency, $\Omega_0$ (Fig. 4b). We note that the population decay rates, $\Gamma$, measured for the repulsive branch (Fig. 3) stay well below the values of $\gamma$, which suggests that collision-induced decoherence is the main damping mechanism.

Figure 4c shows the measured values for the Rabi frequency normalized to $\Omega_0$. The interaction-induced reduction of $\Omega/\Omega_0$ is found to be independent of the particular value of $\Omega_0$ (comparison of blue squares and red dots; see also Supplementary Information). The solid lines show $\sqrt{Z}$ as calculated within our theoretical approach for both the repulsive polaron and the attractive polaron. The comparison with the experimental data demonstrates a remarkable agreement with the relation $\sqrt{Z} = \Omega/\Omega_0$. Our results therefore suggest that measuring the Rabi frequency is a precise and robust way to determine the quasiparticle residue, $Z$, and thus provides a powerful alternative to methods based on the detection of the narrow quasiparticle peak in the spectral response\textsuperscript{16,23}.

In general, our set of spectroscopic methods applies to any resonantly interacting spin or species mixture that can be efficiently radio-frequency-coupled to a weakly interacting one. Such a situation is the rule rather than the exception in ultracold atomic systems\textsuperscript{20}. In mixtures of different species, we anticipate a large variety of suitable systems. For the mass-balanced case of a spin mixture, the well-established $^{40}$K system\textsuperscript{26} would be an obvious choice. We also point out that narrow FRs are more common in the field than broad ones\textsuperscript{20}. Therefore, effects of the finite effective range similar to those described in our work will govern the behaviour of most systems that can be realized in the laboratory. The benefit of an increased lifetime could help overcome the problem of decay into molecular excitations\textsuperscript{11,19} in the experimental investigation of metastable many-body states that rely on repulsive interactions, such as phase-separated states of two fermionic components\textsuperscript{6–8,10,11}. 

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**Figure 3** | Decay rate of the repulsive polaron. The data points display the measured decay rates, $\Gamma$, as extracted by exponential fits to decay curves; the error bars indicate the fit uncertainties. Sample decay curves are shown in the inset. The solid lines represent theoretical calculations of the two-body decay into the attractive polaron (blue line) and the three-body decay into the MHC (red line).

**Figure 4** | Rabi oscillations and the quasiparticle residue. a, Sample Rabi oscillations (for $-1/\kappa\alpha = -1.25$ (magenta points) and $-1/\kappa\alpha = -0.5$ (green points)) with harmonic oscillator fits (solid lines) demonstrate the two effects of the interaction with the Fermi sea: damping and a reduction of the Rabi frequency. The black curve (REF) is a reference curve recorded without $^6$Li. b, c, Damping rates, $\gamma$ (b), and the normalized Rabi frequencies, $\Omega/\Omega_0$ (c), as measured for two different values of the radio-frequency power: $\Omega_0 = 2\pi \times 6.5$ kHz (blue) and $2\pi \times 12.6$ kHz (red). The error bars indicate the fit uncertainties. The solid lines represent the theoretical behaviour of $\sqrt{Z}$ for the repulsive polaron (left) and the attractive polaron (right).
METHODS SUMMARY

A cloud of \(2 \times 10^4\) \(^{40}\)K atoms is confined in an optical dipole trap together with a \(^6\)Li Fermi sea of \(3.5 \times 10^4\) atoms, at a temperature of \(T = 290\) nK. The K atoms reside in the centre of the much larger Li cloud and thus sample a nearly homogeneous Li environment. The relevant energy scale is given by the Li Fermi energy averaged over the K density distribution, \(\epsilon_B = h^2 / 2m_k \times 1.8 \mu K\).

The FR is fully characterized by the parameters \(B_0 = 154.719\) G (centre), \(\Delta B = 0.88\) G (width), \(\sigma_B = 63.6\) (background scattering length) and \(\delta \mu / \hbar = 2.3\) MHz G\(^{-1}\) (differential magnetic moment). The scattering length can be calculated from the standard expression \(a(B) = a_0(1 - \Delta B/(B - B_0))\), and the range parameter \(\frac{\pi^2}{15}\) is obtained as \(R^* = R/\sqrt{15a_0\sigma_B/\Delta B} = 2.790 a_0\), where \(R^*\) is the reduced mass of the K–Li pair. We note that the common textbook definition of the effective range corresponds to \(r_a = -2R^*,\) for \(a \approx \infty\).

The radio-frequency pulses used in measuring the data in Figs 2 and 3 were Blackman-shaped to avoid side lobes in the spectrum. The pulses were 1 ms (duration between 150 and 500 \(\mu\)s) was used to drive the impurity from state \(\mid 0 \rangle\) to state \(\mid 1 \rangle\), selectively creating repulsive polarons. A second, 60-\(\mu\)s, \(\pi\)-pulse transferred the population remaining in state \(\mid 0 \rangle\) into a third state. A third pulse, equal to the first one, transferred the state-\(\mid 1 \rangle\) polarons back into state \(\mid 0 \rangle\), where they were finally measured using spin-state-selective absorption imaging. The measurements shown in Fig. 4 were performed with simple square pulses.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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**METHODS**

**Experimental conditions.** Our system consists of $2 \times 10^4 \text{ } ^{40}\text{K}$ atoms and $3.5 \times 10^3 \text{ } ^6\text{Li}$ atoms confined in an optical dipole trap. The trap is realized with two crossed beams derived from a 1.064-nm single-mode laser source. The measured trap frequencies for Li and K are respectively $v_\ell = 690$ and 425 Hz radially and $v_z = 86$ and 52 Hz axially; this corresponds to a cigar-shaped sample with an aspect ratio of about eight. The preparation procedure is described in detail in ref. 31. The Fermi energies, according to the common definition for harmonic traps, $E_F = \hbar^2 (6N\gamma)^{1/2}$, are $E_F^{\text{Li}} = \hbar \times 44 \text{ kHz} = k_B \times 2.1 \text{ } ^6\text{Li}$ and $E_F^{\text{K}} = \hbar \times 10.4 \text{ kHz} = k_B \times 500 \text{ nK}$. At a temperature of $T = 290 \text{ nK}$, the $^6\text{Li}$ component forms a deeply degenerate Fermi sea ($k_B T / E_F^{\text{Li}} = 0.14$) whereas the $^{40}\text{K}$ component is moderately degenerate ($k_B T / E_F^{\text{K}} = 0.6$).

**Effective Fermi energy.** The $^{40}\text{K}$ atoms sample a nearly homogeneous $^6\text{Li}$ environment. This is because the optical trapping potential for $^{40}\text{K}$ is about twice as deep as for $^6\text{Li}$ and the $^{40}\text{K}$ cloud is confined to the centre of the much larger $^6\text{Li}$ Fermi sea. This allows us to describe the system in terms of the effective Fermi energy, $E_F$, defined as the mean Fermi energy experienced by the $^{40}\text{K}$ atoms. We find that $E_F = \hbar \times 37 \text{ kHz}$, with two effects contributing to the fact that this value is about 15% less than $E_F^{\text{Li}}$. The finite temperature reduces the $^6\text{Li}$ density in the trap centre, leading to a peak local Fermi energy of $\hbar \times 40 \text{ kHz}$. Moreover, the $^{40}\text{K}$ atoms sample a small region around the trap centre, where the density and local Fermi energy are somewhat lower than in the centre. The distribution of Fermi energies experienced by the $^{40}\text{K}$ cloud, that is, the residual inhomogeneity of our system, can be quantified in terms of a standard deviation of $\hbar \times 1.9 \text{ kHz}$.

**Concentration.** The mean impurity concentration (mean number density ratio, $n_{\text{K}}/n_{\text{Li}}$) is about 0.4, if both spin states of the population of K atoms are considered. This may be too large a-priori to justify the interpretation of our data in terms of the low-concentration limit. We find that this interpretation is nevertheless valid, as we take advantage of several facts. Under strongly interacting conditions, only a fraction of the K atoms are transferred into spin state $|1\rangle$ (Fig. 2), which reduces the concentration of interacting impurities. A recent quantum Monte Carlo calculation of the equation of state of a zero-temperature $^6\text{Li}-^{40}\text{K}$ Fermi–Fermi mixture further supports our interpretation in the low-concentration limit: the strongest interaction in the mass-imbalanced system is expected when there are about 4 times more $^{40}\text{K}$ atoms than $^6\text{Li}$ atoms, and for concentrations up to a value of 1 the interaction energy per $^{40}\text{K}$ atom is expected to remain essentially constant. To support our basic assumption with experimental data, we also measured radio-frequency spectra for variable numbers of $^{40}\text{K}$ atoms, confirming that finite-concentration effects remained negligibly small in the relevant parameter range.

**Interaction control through Feshbach resonance.** The FR used for interaction tuning is discussed in detail in refs 21, 32. It is present for $^4\text{Li}$ in the lowest spin state ($F = 1/2$, $m_F = +1/2$) and for $^{40}\text{K}$ in the third-to-lowest spin state ($F = 9/2$, $m_F = -5/2$). The latter represents our interacting state, $|1\rangle$. The neighbouring state with $m_F = -7/2$ serves as state $|0\rangle$; here the interspecies scattering length (about $+65a_0$) is so small that any interaction can be neglected to a good approximation. The tunable scattering length for state $|1\rangle$ in the Fermi sea is well described by the standard formula, $a = a_{bg}(1 - AB(B - B_0))$, with $a_{bg} = 63.0a_0$, $AB = 0.88 \text{ G}$ and $B_0 = 154.719(2) \text{ G}$. The value given for $B_0$ refers to the particular optical trap used in the present experiments, as it includes a small shift induced by the trapping light. The value therefore deviates somewhat from the one given in refs 21, 32. In free space, without the light shift, the resonance centre is located at 154.698(5) G. The uncertainties given for the resonance centre, $B_0$ ($2 \text{ mG}$ in the trapped case and $5 \text{ mG}$ for free space), correspond to standard deviations, obtained from analysing molecule association spectra for various trap settings.

**Character of the resonance.** The character of the resonance is closed-channel dominated. Following the definition of a range parameter, $R^* = R/(2m_0\gamma_0\delta\mu\Delta)$, where $m_0 = m_0 m_u/(m_u + m_0)$ is the reduced mass and $\delta\mu/h = 2.3 \text{ MHz} G^{-1}$ is the differential magnetic moment, the resonance is characterized by $R^* = 2700\Delta_0$. For $a \rightarrow \infty$, this parameter corresponds to the common textbook definition of the effective range, $r_e = -2R^*$. Our value for $R^*$ coincidentally lies very close to $1/k_B = 2.850\Delta_0$, which means that the strongly interacting regime corresponds roughly to the universal range of the resonance. Our system therefore represents an intermediate case ($k_R R^* = 0.95$), where the behaviour is near universal, but with significant effects arising from the finite effective range.

**Details on radio-frequency pulses.** To measure the data in Fig. 2, we used Blackman pulses to avoid side lobes in the spectrum. For Fig. 2a, the pulses were 1-ms long (spectral width, $0.7 \text{ kHz} = 0.037E_F^{\text{Li}}$) and the radio-frequency power was adjusted such that $\pi$-pulses would be realized in the absence of interactions with the Fermi sea. For the data in Fig. 2b, the radio-frequency power was increased by a factor of 100 and the pulse duration was set to 0.5 ms. This resulted in pulses with an area of $\pi$ without the Fermi sea. For the lifetime measurements in Fig. 3, we used a sequence of three Blackman pulses. The first pulse (duration between 150 and 500 $\mu$s) was set to drive the non-interacting impurity from spin state $|0\rangle$ ($m_F = -7/2$) into state $|1\rangle$ ($m_F = -5/2$); here the frequency was carefully set to resonantly create repulsive polarons and the pulse area was set to fulfill the $\pi$-pulse condition. The second pulse was a short (60-$\mu$s) cleaning pulse, which removed the population remaining in $|0\rangle$ by transferring it to another, empty, spin state ($m_F = 9/2$). The third pulse had the same parameters as the first one and resonantly transferred the population of the polaronic state in $|1\rangle$ back to the non-interacting state, $|0\rangle$, where it was finally measured by spin-state-selective absorption imaging. The measurements of Rabi oscillations in Fig. 4 were performed with simple square pulses.

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