The dynamics of a single impurity in an environment is a fundamental problem in many-body physics. In the solid state, a well-known case is an impurity coupled to a bosonic bath (such as lattice vibrations); the impurity and its accompanying lattice distortion form a new entity, a polaron. This quasiparticle plays an important role in the spectral function of high-transition-temperature superconductors, as well as in colossal magnetoresistance in manganites. For impurities in a fermionic bath, studies have considered heavy or immobile impurities which exhibit Anderson’s orthogonality catastrophe and the Kondo effect. More recently, mobile impurities have moved into the focus of research, and they have been found to form new quasiparticles known as Fermi polarons. The Fermi polaron problem constitutes the extreme, but conceptually simple, limit of two important quantum many-body problems: the crossover between a molecular Bose-Einstein condensate and a superfluid with BCS quantum many-body problems: the crossover between a molecular Bose-Einstein condensate and a superfluid with BCS antiferromagnetism. It has very recently been theoretically proposed that such quantum phases (and other elusive exotic states) might become realizable in Fermi gases confined to two dimensions. Their stability and observability are intimately related to the theoretically debated properties of the Fermi polaron in a two-dimensional Fermi gas. Here we create and investigate Fermi polarons in a two-dimensional, spin-imbalanced Fermi gas, measuring their spectral function using momentum-resolved photoemission spectroscopy. For attractive interactions, we find evidence for a disputed pairing transition between polarons and tightly bound dimers, which provides insight into the elementary pairing mechanism of imbalanced, strongly coupled two-dimensional Fermi gases. Additionally, for repulsive interactions, we study novel quasiparticles—repulsive polarons—the lifetime of which determines the possibility of stabilizing repulsively interacting Fermi systems.

Spin-imbalanced Fermi gases exhibit a wealth of complex pairing phenomena because the Fermi surfaces of the two spin components are mismatched. Well-known examples are the predicted Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) pairing mechanism, in which Cooper pairs form at finite momentum, and the Chandrasekhar-Clogston limit of BCS superconductivity. In the extreme case of spin-imbalance, just one mobile spin-up particle is immersed in a large spin-down Fermi sea. New quasiparticles, so-called Fermi polarons, are formed by the impurity being coherently dressed with particle-hole excitations of the majority component. For weak attractive interactions, the new many-body ground state is the attractive Fermi polaron (see Fig. 1, which corresponds to the limit of a partially polarized Fermi gas. If the attraction between impurity and majority component is sufficiently strong, and depending on the dimensionality, the attractive polaron may undergo a transition to a locally paired dimer state. This corresponds to the limiting case of phase separation between a fully polarized Fermi gas and a balanced superfluid state. The opposite situation of an impurity interacting repulsively with the fermionic bath is notably different. For short-range interactions, strong repulsion between particles can only be achieved if the underlying interaction potential is attractive, which implies a two-particle bound state with binding energy . Repulsive impurities are therefore metastable and eventually decay either into a bound state or into an attractive polaron with the simultaneous creation of particle and hole excitations. It has very recently been theoretically proposed that a repulsively interacting impurity, despite its metastability, still forms a...
well-defined quasiparticle, the repulsive polaron, which has not been observed in solid state systems so far. Its lifetime is of critical importance in pairing instabilities of repulsively interacting Fermi gases\(^{20,21}\) and in the approach to observing the Stoner transition of itinerant ferromagnetism\(^9\).

Dimensionality plays an important role in the physics of the Fermi polaron because quantum fluctuations, such as the creation of particle–hole pairs, are enhanced in low dimensions and affect the many-body ground state. In three dimensions, the properties of the Fermi polaron and the transition between polaron and molecule were predicted theoretically\(^{4,8,22–24}\), and attractive\(^7\)–\(^7\) as well as repulsive\(^7\) polarons have been observed experimentally. In one dimension, the exact solution of the spin–impurity Hamiltonian displays no transition for any interaction strength\(^{25}\). The most interesting, yet unresolved, scenario is the two-dimensional scattering length (see Methods). For weak repulsive interaction, the effective mass, which we interpret as the polaron–molecule transition point, increases linearly with the r.f. amplitude. Error bars correspond to 1 s.d. uncertainty in the fit.

Here we report the creation of Fermi polarons by immersing a few spin-down impurity atoms in a two-dimensional Fermi sea of spin-up atoms. This strongly spin-imbalanced Fermi gas is formed by a 85/15 mixture of the two lowest Zeeman states \(\mid -9/2 \rangle \) and \(\mid -7/2 \rangle\) of the \(F = 9/2\) hyperfine manifold of \(^{40}\)K confined to two dimensions with an optical lattice\(^{26}\). We adiabatically prepare the attractive ground state, and, independently, the repulsive branch, and measure their single particle spectral functions \(A(k, E)\) using momentum-resolved photo-emission spectroscopy\(^{17–19}\) (see Methods). Here, \(k\) and \(E\) are the wave vector and the energy of the single particle excitation, respectively. This methodology allows us to study the many-body state in equilibrium and is in contrast to ‘inverse’ radio frequency (r.f.) spectroscopy\(^{26,27}\), which probes the transient creation of excitations. Additionally, the single particle spectral function gives access to the full quasiparticle dispersion, which is averaged out in momentum-integrated r.f. spectroscopy\(^{25,28}\).

The attractive polaron is formed by a coherent dressing of the quasiparticle because quantum fluctuations, such as the creation of particle–hole pairs, are enhanced in low dimensions and affect the many-body ground state. In three dimensions, the properties of the Fermi polaron and the transition between polaron and molecule were predicted theoretically\(^{4,8,22–24}\), and attractive\(^7\)–\(^7\) as well as repulsive\(^7\) polarons have been observed experimentally. In one dimension, the exact solution of the spin–impurity Hamiltonian displays no transition for any interaction strength\(^{25}\). The most interesting, yet unresolved, scenario is the two-dimensional scattering length (see Methods). For weak repulsive interaction, the effective mass, which we interpret as the polaron–molecule transition point, increases linearly with the r.f. amplitude. Error bars correspond to 1 s.d. uncertainty in the fit.

In Fig. 1b–d we display the measured single particle spectral function for different values of the interaction parameter, \(\ln(k_F a_{2D})\). Here, \(k_F\) denotes the Fermi wave vector of the majority component and \(a_{2D}\) the two-dimensional scattering length (see Methods). For weak attractive interaction in the polaronic regime, we observe a symmetric line shape as a function of energy for every wave vector \(k\), which signals a well defined quasiparticle, the attractive polaron (see Fig. 1b). In the molecular regime we find a weak, asymmetric spectrum, which is skewed with a tail to lower energies (see Fig. 1d). This spectrum is dominated by a broad incoherent background, which has contributions from incoherent particle–hole excitations and molecules.

In Fig. 2 we display our measurements of the quasiparticle energy \(E_0\) (Fig. 2a) and the effective mass \(m^*\) (Fig. 2b) for the attractive polaron branch. We determine the energy \(E_{\text{peak}}(k)\) of the maximum of the spectral function \(A(k, E)\) at a wave vector \(k\) and use the fit function \(E_{\text{peak}}(k) = E_0 + \hbar^2 k^2(1/m^* - 1/m)/2\), with \(m\) being the bare mass, in order to determine the quasiparticle energy \(E_0\) and the effective mass \(m^*\). We find very good agreement with the theory of ref. 15 for the effective mass and the quasiparticle energy for data above \(\ln(k_F a_{2D}) = -0.4\). For data below this value, we observe a divergence of the effective mass, which we interpret as the polaron–molecule transition having been crossed. The polaron–molecule transition in strictly two dimensions has been predicted\(^{12}\) at \(\ln(k_F a_{2D}) = -0.8\) and in quasi-two dimensions\(^{29}\) \(\ln(k_F a_{2D}) = -0.6\). Effects of averaging over the inhomogeneous density profile, final state interactions, finite temperature, and finite concentration of impurities may affect this value and shift the transition point to larger values of \(\ln(k_F a_{2D})\). The polaron–molecule transition has only a very weak effect on the energy spectrum, as has been already pointed out theoretically in three dimensions\(^4\), because the polaron and molecule energy curves are crossing at a very shallow angle (see Fig. 1a). We observe a gradual deviation of the quasiparticle energy from theory (Fig. 2a inset) which, at least in part, could be attributed to finite range corrections to the interatomic potential.

The attractive polaron is formed by a coherent dressing of the impurity with particle–hole excitations of the majority component. We investigate its coherence by driving Rabi oscillations between the polaron and the weakly interacting final state (Fig. 2c). When the r.f.
frequency is tuned to the polaron resonance in the spectrum, we observe coherent oscillations of the transferred number of atoms as we increase the amplitude of the r.f. coupling for a fixed duration. In contrast, when the r.f. frequency is tuned to the incoherent background we do not observe oscillations but only a linear increase in signal strength.

Polarons are well-defined quasiparticles only at low temperature and in the limit of a single impurity. We investigate the deviations from this idealized picture in Fig. 3. Thermal excitations lead to decoherence of the dressing cloud and energetically higher-lying states, such as the molecular branch (see Fig. 1a), may be occupied. In the weakly interacting limit, the molecular branch is approximately \( E_F \) above the polaronic state; however, this energy difference reduces as the polaron–molecule transition is approached. Hence we expect the effects of temperature to be most pronounced near the polaron–molecule transition, and we focus our investigations on this regime. Indeed, we find that at \( \ln(k_{F}d_{2D}) = 0.45(5) \) (red squares in Fig. 3a) the effective mass remains unaffected by temperature up to \( T/T_F = 0.5 \), whereas for \( \ln(k_{F}d_{2D}) = -0.07(3) \) (blue circles in Fig. 3a) we observe a significant change of the single particle spectrum. At low temperatures we find good agreement with the zero-temperature prediction, but at higher temperatures the effective mass increases. This could signal a transition from a polaron at low temperature into the incoherent molecule transition, and we focus our investigations on this regime. We extract the lifetime by a fit (dashed line). The solid line is the theoretical prediction from ref. 16. The grey shaded area reflects the range of lifetime, energy and effective mass for both interaction strengths.

Finally, we turn our attention to the repulsive polaron. This quasi-particle plays a decisive role in the question of whether itinerant ferromagnetism can be achieved with repulsive short-range interactions between fermions, which has been argued to be impossible in a three-dimensional spin-1/2 mixture with contact interactions. The recent observation of a repulsive polaron in a three-dimensional heteronuclear Fermi–Fermi mixture has renewed the interest in whether mass-imbalance and/or reduced dimensionality could stabilize the formation of polarized domains. We access the repulsive branch of the Feshbach resonance between the \( | -9/2 \rangle \) and \( | -5/2 \rangle \) states near 224 G (see Methods). Lifetime, energy and effective mass are extracted from the spectral function \( A(k, E) \), which we measure after different hold times.

For the lifetime measurement (Fig. 4a), we determine the atom number loss, integrating from \(-10 \text{ kHz}\) to \(+10 \text{ kHz}\). We observe a

![Figure 3](image-url) **Figure 3** | Finite temperature and impurity concentration. **a**, Effective mass as a function of temperature for \( \ln(k_{F}d_{2D}) = 0.45(5) \) (red squares) and \( \ln(k_{F}d_{2D}) = -0.07(3) \) (blue circles). The solid horizontal lines show the theoretical prediction at zero temperature. All data are taken for \( C = 0.13 \). **b**, Effective mass as a function of impurity concentration. The horizontal lines show the theoretical prediction for the polaron and the shaded bars reflect the variation of the Fermi energy for the different measurements. Data are taken at \( T/T_F = 0.25(3) \). Error bars correspond to 1 s.d. uncertainty in the fit.

![Figure 4](image-url) **Figure 4** | Repulsive polaron. **a**, Lifetime of the repulsive branch. The inset shows an example of a time-resolved measurement at \( \ln(k_{F}d_{2D}) = -1.2 \) from which we extract the lifetime by a fit (dashed line). The solid line is the theoretical prediction from ref. 16. The grey shaded area reflects the range of Fermi energies of \((11 \pm 1) \text{ kHz}\). **b, c**, Measured energy (b) and effective mass (c). Error bars correspond to 1 s.d. uncertainty in the fit.
fast decay (Fig. 4a inset) to a plateau which decays much more slowly, similar to the balanced case in three dimensions^{14}. In Fig. 4a we display the measured lifetime τ of the repulsive branch as a function of the interaction strength, which agrees with the theoretical prediction for the lifetime of the repulsive polaron^{14}, adapted for the quasi-two-dimensional binding energy E_B and quasi-two-dimensional scattering length a_F (see Methods). In the regime of strong interactions (small negative ln(k_Fd_{pp})), the decay rate 1/τ becomes a sizeable fraction of E_F, qualitatively similar to repulsive Fermi gases in three dimensions^{14}. The energy and the effective mass are extracted from the spectral function as above and they are plotted in Fig. 4b and c, respectively. Both mass and energy deviate from the prediction for the homogeneous gas under exact two-dimensional confinement^{15,16}, for which we replace the exact two-dimensional binding energy with the quasi-two-dimensional binding energy. The repulsive polaron energy is in qualitative agreement with the trap-averaged spectra of ref. 15, which have revealed a relatively small dependence of the polaron energy on the interaction parameter. To model our data quantitatively, it might be necessary to include final-state interaction effects, to use a quasi-two-dimensional theory^{29} including harmonic confinement, and to include possible effects of non-adiabaticity and the formation time of the polaron during the relatively fast magnetic field ramp.

In conclusion, we have observed features of attractive and repulsive Fermi polarons in two dimensions. We find evidence for the polaron–molecule transition in a two-dimensional Fermi gas, although at a slightly different interaction parameter than theoretically predicted. The future inclusion of a localized, potentially spin-dependent, potential will allow the effective mass of the impurity to be increased, and to move into the regime of X-ray edge phenomena and the Kondo effect, in which the internal spin degree of freedom of an immobile impurity becomes entangled with the Fermi sea.

**METHODS SUMMARY**

The starting point of this work is a quantum degenerate Fermi gas of ^40^K atoms in a strongly mixed background with an impurity concentration C = 0.15 of the two lowest Zeeman states |−9/2⟩ and |−7/2⟩ (for the repulsive polaron |−9/2⟩ and |−5/2⟩) of the F = 9/2 hyperfine manifold confined to an optical lattice. The average Fermi energy of the majority component is E_F/k_B = 10 K and the temperature is typically T = 0.2 K. We record momentum-resolved photoemission spectra near the Feshbach resonance at 202.1 G (224.2 G) by coupling the |−7/2⟩ (|−5/2⟩) state to the weakly interacting state |−5/2⟩ (|−3/2⟩) using a r.f. photon of frequency ω_{QF} with negligible momentum transfer. The momentum distribution of the transferred atoms is detected in a time-of-flight experiment and we average the absorption signal azimuthally to obtain the single particle spectral function A(k, E), with the wave vector k = √k^2 + k^2_z and energy E = E_F − Ω_{QF} using the atomic Zeeman energy E_Z.

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

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1. Devreese, J. T. & Alexandrov, A. S. Fröhlich polaron and bipolaron: recent developments. Rep. Prog. Phys. 72, 066501 (2009).
2. Anderson, P. W. Infrared catastrophe in Fermi gases with local scattering potentials. Phys. Rev. Lett. 18, 1049–1051 (1967).
3. Kondo, J. Resistance minimum in dilute magnetic alloys. Prog. Theor. Phys. 32, 37–49 (1964).
4. Prokof’ev, N. & Svistunov, B. Fermi-polaron problem: diagrammatic Monte Carlo method for divergent sign-alternating series. Phys. Rev. B 77, 020408 (2008).
5. Schirozék, A., Wu, C.-H., Sommer, A. & Zwierlein, M. W. Observation of Fermi polarons in a tunable Fermi liquid of ultracold atoms. Phys. Rev. Lett. 102, 230402 (2009).
6. Nascimbène, S. et al. Collective oscillations of an imbalanced Fermi gas: axial compression modes and polaron effective mass. Phys. Rev. Lett. 103, 170402 (2009).
7. Kollath, C. et al. Metastability and coherence of repulsive polarons in a strongly interacting Fermi mixture. Preprint at http://arXiv.org/abs/1112.0202 (2011).
8. Chevy, F. & Mora, C. Ultra-cold polarized Fermi gases. Rep. Prog. Phys. 73, 112401 (2010).
9. Dume, R.A. & MacDonald, A. H. Itinerant ferromagnetism in an ultracold atom Fermi gas. Phys. Rev. Lett. 95, 230403 (2005).
10. Chubukov, A. V. Kohn-Luttinger effect and the instability of a two-dimensional repulsive Fermi liquid at T=0. Phys. Rev. B 48, 1097–1104 (1993).
11. Conduit, G. J., Conlon, P. H. & Simons, B. D. Superfluidity at the BEC-BCS crossover in two-dimensional Fermi gases with population and mass imbalance. Phys. Rev. A 77, 053617 (2008).
12. Parish, M. M. Polaron-molecule transitions in a two-dimensional Fermi gas. Phys. Rev. A 83, 051603 (2011).
13. Zöllner, S., Bruun, G. M. & Pethick, C. J. Polarons and molecules in a two-dimensional Fermi gas. Phys. Rev. A 83, 021603 (2011).
14. Klawunn, M. & Recati, A. Fermi polaron in two dimensions: Importance of the two-body bound state. Phys. Rev. A 84, 033607 (2011).
15. Schmidt, R., Enss, T., Pietila, V. & Demler, E. Fermi polarons in two dimensions. Phys. Rev. A 85, 021602(R) (2012).
16. Ngampruetikorn, V., Lewenstein, J. & Parish, M. M. Repulsive polarons in two-dimensional Fermi gases. Preprint at http://arXiv.org/abs/1110.6415 (2011).
17. Dao, T.-L., Georges, A., Dalibard, J., Salomon, C. & Carusotto, I. Measuring the one-particle excitations of ultracold Fermionic atoms by stimulated Raman spectroscopy. Phys. Rev. Lett. 98, 240402 (2007).
18. Stewart, J. T., Gaebler, J. P. & Jin, D. S. Using photoemission spectroscopy to probe a strongly interacting Fermi gas. Nature 454, 744–747 (2008).
19. Feld, M., Frohlich, B., Vogt, E., Koschorreck, M. & Köhl, M. Observation of a pairing pseudogap in a two-dimensional Fermi gas. Nature 480, 75–78 (2011).
20. Cui, X. & Zhai, H. Stability of a fully magnetized ferromagnetic state in repulsively interacting ultracold Fermi gases. Phys. Rev. A 81, 041602 (2010).
21. Pietila, V., Pekker, D., Nishida, Y. & Demler, E. Pairing instabilities in quasi-two-dimensional Fermi gases. Phys. Rev. A 85, 023621 (2012).
22. Lobo, C., Recati, A., Giorgini, S. & Stringari, S. Normal state of a polarized Fermi gas at unitarity. Phys. Rev. Lett. 97, 200403 (2006).
23. Funk, M., Dumitrescu, P. T. & Zwenger, W. Polaron-to-molecule transition in a strongly imbalanced Fermi gas. Phys. Rev. A 80, 053605 (2009).
24. Pilati, S., Bertaina, G., Giorgini, S. & Troyer, M. Itinerant ferromagnetism of a repulsive atomic Fermi gas: a quantum Monte Carlo study. Phys. Rev. Lett. 105, 030405 (2010).
25. McGuire, J. B. Interacting Fermions in one dimension. II. Attractive potential. J. Math. Phys. 7, 123–132 (1966).
26. Frohlich, B. et al. Radiofrequency spectroscopy of a strongly interacting two-dimensional Fermi gas. Phys. Rev. Lett. 106, 105301 (2011).
27. Schmidt, R. & Enss, T. Excitation spectra and rf response near the polaron-to-molecule transition from the functional renormalization group. Phys. Rev. A 83, 063620 (2011).
28. Sanner, C. et al. Correlations and pair formation in a repulsively interacting Fermi gas. Preprint at http://arXiv.org/abs/1108.2017 (2011).
29. Supplementary Information is linked to the online version of this article at www.nature.com/nature.

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to M. Köhl (mk540@cam.ac.uk).

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**METHODS**

**Preparation of imbalanced 2D gases.** We prepare degenerate Fermi gases following the general procedure of ref. 26. Additionally, during the evaporative cooling sequence we apply an r.f. pulse in order to prepare the desired spin mixture by selectively removing atoms from the \(|-7/2\rangle\) state. Subsequently, we load the imbalanced mixture into an optical lattice formed by a horizontally propagating, retro-reflected laser beam of wavelength \(\lambda = 1.064\) nm, focused to a waist (1/e² radius) of 140 \(\mu\)m. We increase the laser power over a time of 200 ms to reach the final potential depth with a trapping frequency along the strongly confined direction of \(\omega = 2\pi \times 78.5\) kHz. After loading the optical lattice, we adiabatically reduce the power of the optical dipole trap such that the atoms are confined only by the Gaussian intensity envelope of the lattice laser beams. The resulting radial trapping frequency of the two-dimensional gases is \(\omega_r = 2\pi \times 127\) Hz. Along the axial direction we populate approximately 30 layers of the optical lattice potential with an inhomogeneous peak density distribution. The Fermi energy (of the majority component) is the measured, density-weighted average across the different layers. We measure that majority and minority component have the same absolute temperature. As a result, the minority atoms occupy fewer layers and experience a more uniform peak density of majority atoms.

**Momentum-resolved photoemission spectroscopy.** In order to access the attractive polaron branch, we adiabatically increase the interaction strength by lowering the magnetic field in 30 ms from 209 G to a value near the Feshbach resonance at 202.1 G. Momentum resolved photoemission spectroscopy is performed by applying an r.f. pulse near 50 MHz with a Gaussian amplitude envelope with a full-width at half-maximum of 280 \(\mu\)s to transfer atoms from the \(|-7/2\rangle\) state to the \(|-5/2\rangle\) state. Atoms in the \(|-5/2\rangle\) state have a two-body scattering length of 250 Bohr radii with the \(|-9/2\rangle\) state\(^8\). We turn off the optical lattice 100 \(\mu\)s after the r.f. pulse, switch off the magnetic field, and apply a magnetic field gradient to achieve spatial splitting of the three spin components in a Stern-Gerlach experiment. We have experimentally verified that the spectra and the extracted data do not vary when an additional wait time of 8 ms is introduced after the magnetic field ramp.

The repulsive polaron branch is accessed by preparing the imbalanced \(|-9/2\rangle/|-7/2\rangle\) mixture at a magnetic field of 220 G and spin-flipping the atoms from \(|-7/2\rangle\) to \(|-5/2\rangle\) using a 30-\(\mu\)s-long r.f. pulse with 95% transfer efficiency. The pulse is tuned to the bare Zeeman transition energy but is broadband to include also the repulsive polaron energy shift. Then, we ramp the magnetic field to the desired value near the \(|-9/2\rangle/|-5/2\rangle\) Feshbach resonance in 5 ms. We apply a r.f. pulse near 53 MHz with a Gaussian amplitude envelope with a full-width at half-maximum of 270 \(\mu\)s to transfer atoms from the \(|-5/2\rangle\) state to the \(|-3/2\rangle\) state. The scattering length between the \(|-9/2\rangle\) and \(|-3/2\rangle\) states at this magnetic field is approximately 190 \(a_B\), where \(a_B\) is the Bohr radius. The sequence is completed using absorption imaging of the expanding clouds after Stern-Gerlach separation in an inhomogeneous field.

For each experimental run, the magnetic field is calibrated using spin-rotation with an r.f. pulse of an imbalanced mixture on the \(|-9/2\rangle/|-7/2\rangle\) transition. The magnetic field accuracy deduced from these measurements is \(<3\) mG. We measure the temperature by ballistic expansion of a weakly interacting gas, and the quoted numbers refer to the average of \(T/T_F\) across the whole sample.

**Interaction parameter in two dimensions.** Two particles in a two-dimensional system created by tight harmonic confinement exhibit a confinement-induced bound state of binding energy \(E_B\). The binding energy is linked to the three-dimensional scattering length \(a_s\) and is obtained from the transcendental equation\(^{11-12}\):

\[
l_s/a_s = \int_0^{\infty} \frac{du}{\sqrt{4\pi u}} \left(1 - \frac{\exp(-E_B u/\hbar\omega)}{\sqrt{1 - \exp(-2u)}}\right)
\]

Here \(l_s = \sqrt{\hbar/ma_s}\) is the harmonic oscillator length, and \(a_s\) is determined using the following parameters of the Feshbach resonances: Feshbach resonance between \(|-9/2\rangle\) and \(|-7/2\rangle\): \(B_0 = 202.1\) G, \(\Delta B = 7\) G and \(a_0 = 174\) \(a_B\) and Feshbach resonance between \(|-9/2\rangle\) and \(|-5/2\rangle\): \(B_0 = 224.2\) G, \(\Delta B = 7.5\) G and \(a_0 = 174\) \(a_B\). Using \(E_B\) we define the two-dimensional scattering length \(a_{2D}\) by \(E_B = \hbar^2/a_{2D}^2\).

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31. Petrov, D. & Shlyapnikov, G. Interatomic collisions in a tightly confined Bose gas. Phys. Rev. A 64, 012706 (2001).
32. Bloch, I., Dalibard, J. & Zwerger, W. Many-body physics with ultracold gases. Rev. Mod. Phys. 80, 885-964 (2008).