Phase diagram of a two-component Fermi gas with resonant interactions

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The pairing of fermions is at the heart of superconductivity and superfluidity. The recent experimental realization of strongly interacting atomic Fermi gases has opened a new, controllable way to study novel forms of pairing and superfluidity. A major controversial issue has been the stability of superfluidity against an imbalance between the two spin components when the fermions interact resonantly. Here we present the phase diagram of a spin-polarized Fermi gas of $^6$Li atoms at unitarity, mapping out the superfluid phase versus temperature and density imbalance. Using tomographic techniques, we reveal spatial discontinuities in the spin polarization, the signature of a first-order superfluid-to-normal phase transition, which disappears at a tricritical point where the nature of the phase transition changes from first-order to second-order. At zero temperature, there is a quantum phase transition from a fully-paired superfluid to a partially-polarized normal gas. These observations and the implementation of an in situ ideal gas thermometer provide quantitative tests of theoretical calculations on the stability of resonant superfluidity.

Superfluidity and superconductivity of fermions are based on the formation of fermion pairs. The stability of these pairs determines the robustness of the superfluid state, and the quest for superconductors with high critical temperature is a search for systems with strong pairing mechanisms. Ultracold atomic Fermi gases present a highly controllable model system for studying strongly interacting fermions \[\uparrow\downarrow\text{]. Tunable interactions utilizing Feshbach collisional resonances and control of population or mass imbalance among the spin components provide unique opportunities to investigate the stability of pairing \[\uparrow\downarrow\text{ and possibly to search for new exotic forms of superfluidity [5, 6]. The case of unitarity, when the two spin components resonantly interact and the behavior of the system becomes independent of the nature of the interactions, has become a benchmark for experimental and theoretical studies over the last few years. However, there is an ongoing debate about the stability of resonant superfluidity, reflected in major discrepancies in predicted transition temperatures for the balanced spin mixture \[\uparrow\downarrow\text{ of second-order. The two regimes are connected by a tricritical point \[\uparrow\downarrow\text{ for which we estimate the position as \((\sigma_{tc}, T_{tc}/T_{F\uparrow}) \approx (0.2, 0.07)\), where \(k_B T_{F\uparrow} = \hbar^2 (6\pi^2 n_{\uparrow})^{2/3}/2m\) is the Fermi energy of the majority component of density \(n_{\uparrow}\) \((k_B\text{ is the Boltzmann constant, } \hbar\text{ is the Planck constant divided by } 2\pi\text{ and } m\) is the atomic mass of \(^6\text{Li}). Our low-temperature results confirm a zero-temperature quantum phase transition at a critical polarization \(\sigma_{tc} \approx 0.36\).

This work required the introduction of several novel techniques. A tomographic reconstruction of local Fermi temperatures and spin polarization allowed us to obtain the phase diagram for the homogeneous system, no longer affected by the inhomogeneous density of the trapped samples. Furthermore, absolute temperatures were obtained using in situ thermometry applied to the non-interacting fully-polarized Fermi gas in the outer part of the trapped samples, an ideal thermometer with exactly-known thermal properties. In contrast to previous works \[\uparrow\downarrow\text{, this is a direct measurement without any approximations.

Spatial structure of a trapped Fermi mixture
Our experiments are carried out in a trapping potential \(V(\vec{r})\). The local chemical potential of each spin component is given as \(\mu_{\uparrow\downarrow}(\vec{r}) = \mu_{1,10}(\vec{r}) - V(\vec{r})\), where \(\mu_{1,10}\) are the global chemical potentials. When \(\mu_{10} \neq \mu_{1}\) due to imbalanced populations, the chemical potential ratio

Here we resolve this long standing debate by present-
\[ \eta(r) = \mu_1 / \mu_1 \] spatially varies over the trapped sample and thus, under the local density approximation (LDA) the trapped inhomogeneous sample is represented by a line in phase diagrams of the homogeneous system. Figure 1 illustrates the spatial structure of a strongly interacting Fermi mixture in a harmonic trap. In the inner region, where \( \eta \) is closer to unity, a superfluid with zero (small) spin polarization will form at zero (low) temperatures, having a sharp phase boundary against the partially-polarized normal gas in the outer region. The spin polarization shows a discontinuity at the phase boundary \( r = R_c \), a signature of the phase separation of a superfluid and a normal gas \[ \text{(24). The critical phase polarization} \begin{align*} \sigma_c &= \lim_{r \to R_c^+} \sigma(r) \quad (\sigma_s = \lim_{r \to R_c^-} \sigma(r)) \end{align*} \] represents the minimum (maximum) spin polarization for a stable normal (superfluid) gas. At higher temperature, the discontinuity in the density imbalance disappears. The main result of this paper is the observation and quantitative analysis of such density profiles. Since we have no experimental evidence, we are not discussing the exotic partially-polarized phases \[ \text{(29)} \] which could exist only in the transition layer between the superfluid core and the normal outer region.

We prepared a variable spin mixture of the two lowest hyperfine states of \(^6\text{Li}\) atoms, labeled as \( | \uparrow \rangle \) and \( | \downarrow \rangle \), at a magnetic field of 833 G. A broad Feshbach resonance is located at 834 G and the interactions between the two spin states are resonantly enhanced. Our sample was confined in a 3D harmonic trap with cylindrical symmetry. The in situ density distributions of the majority (spin \( | \uparrow \rangle \)) and minority (spin \( | \downarrow \rangle \)) components were determined using a phase-contrast imaging technique. Since the trapped sample was observed to have an elliptical shell structure of the same aspect ratio \( \lambda = f_x / f_z \) as the trapping potential over our entire temperature range, where \( f_x \) (\( f_z \)) is the oscillation frequency in the transverse (axial) direction (Fig. 2), we obtained the low-noise profiles \( \tilde{n}(r) \) by averaging the column density distribution along the equipotential line (defined as \( \lambda^2 x^2 + z^2 = r^2 \) for a given radial position \( r \)). The region for averaging...
Increasing temperature

FIG. 3: Density profiles of trapped Fermi mixtures with imbalanced populations. The first row (a-d) shows the averaged column density profiles for various temperatures (red: majority, blue: minority, black: difference). The majority radius \( R_\uparrow \) was determined from the outer region \((r > R_\uparrow, R_\uparrow \) the radius of the minority cloud) of the majority profiles using a fit to a zero-temperature Thomas-Fermi (TF) distribution (black dotted lines). The column densities are normalized by the central value of the fitted TF distribution. The second row (e-h) and the third row (i-l) show the reconstructed 3D profiles and the spin polarization profiles \( \sigma(r) \) corresponding to the profiles in a-d. The core radius \( R_c \) was determined as the peak (and/or kink) position in the column density difference (only for a-c), indicated by the up arrows and the dashed lines. The two spin polarizations \( \sigma_\uparrow \) at \( r = R_c \) and \( \sigma_\downarrow \) at \( r = R_c - 0.05 R_\uparrow \) are marked by the right and left arrows, respectively. \( T' \), \( \sigma_c \), \( R_c/R_\uparrow \), \( R_\uparrow \) (in \( \mu \text{m} \)), \( N_\uparrow \), \( \delta \) (in \% ) and \( \lambda \) were respectively: (a, e, i) 0.03(1), 0.34, 0.43, 385, 5.9(5) \( \times 10^6 \), 44(4), 6.15; (b, f, j) 0.05(2), 0.24, 0.39, 416, 1.0(1) \( \times 10^7 \), 48(4), 6.5; (c, g, k) 0.07(1), 0.21, 0.29, 443, 1.2(2) \( \times 10^7 \), 54(4), 6.5; (d, h, l) 0.10(1), not determined, not determined \((\sigma_{r=0} = 0.15 \text{ and condensate fraction } = 2(1)\%)\), 398, 5.3(4) \( \times 10^6 \), 54(4), 7.7.

was restricted depending on the type of analysis. The density profiles \( n(r) \) were determined from the 3D reconstruction using the inverse Abel transformation of the column densities \( \hat{n}(r) \) [24]. Deviations from the trap aspect ratio were only found for the outer thermal wings and will be discussed below. More detailed description of the experimental procedure and the image processing is provided in appendix. Most of our measurements were performed at a total population imbalance \( \delta \approx 50\% \), where \( \delta = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow) \) refers to the total atom numbers in the sample, \( N_\uparrow \) and \( N_\downarrow \) of the spin \( \uparrow \) and \( \downarrow \) components, respectively.

Figure 3 displays the radial profiles of the densities \( n_\uparrow(r) \) and \( n_\downarrow(r) \) of each component and the corresponding spin polarization \( \sigma(r) \) for various temperatures. The discontinuity in the spin polarization, clearly shown at very low temperature, demonstrates the phase separation of the inner superfluid of low polarization and the outer normal gas of high polarization. At low temperature the core radius \( R_c \) is determined as the kink (and/or peak) position in the column density difference profile. At high temperature (but still in the superfluid regime), the discontinuity in \( \sigma(r) \) disappears. At our lowest temperature, the radii of the minority cloud and the core region were measured as \( R_\downarrow = 0.73(1) R_\uparrow \) and \( R_c = 0.430(3) R_\uparrow \) (at \( \delta = 44(4)\% \)), respectively, and agree with recent theoretical calculations [10, 29] within the experimental uncertainties due to the determination of \( \delta \). Here, \( R_\uparrow \) is the radius of the majority cloud, measured as \( R_\uparrow \approx 0.95 R_{TF} \) \((R_{TF} \) is the Thomas-Fermi (TF) radius of a non-interacting Fermi gas with the same atom number of \( N_\uparrow \)), reflecting the attraction between the two components.

**Thermometry of a strongly interacting Fermi gas**

In most cold atom experiments, temperature is deter-
FIG. 4: Temperature determination using in situ density profiles. The relative temperature $T' = T/T_{F0}$ (see text for definition) was determined from the outer region ($r > R_1$) of the averaged column density difference profile (black line) fitted to a finite temperature Fermi-Dirac distribution (red line). The radius of the minority cloud $R_1$ was determined from a fit of the wing profile of the minority component (black dashed line) to a zero temperature TF distribution (red dashed line). (a) $T' = 0.03(1)$ and $\delta = 44(4)\%$, and (b) $T' = 0.08(1)$ and $\delta = 46(4)\%$.

...mined from the density distribution after ballistic expansion, reflecting the momentum distribution of thermal atoms in the cloud. In the case of a population-imbalanced Fermi mixture, the outer part of the majority component, having no spatial overlap with the minority component, is a non-interacting Fermi gas in thermal equilibrium with the inner part and fulfills the definition of an ideal thermometer, namely a substance with exactly-understood properties in contact with the sample to be characterized. This concept was first introduced in ref. [15], where temperature was determined from the majority wing profile after expansion. However, we found that during expansion some of the outer majority atoms experience collisions with the minority atoms in the inner region, causing a modification of their kinetic energy (see appendix). We avoided this problem by analyzing the in situ profiles. The outer part of the averaged column density difference profile ($r > R_1$) was fit to a finite temperature Fermi-Dirac distribution in a harmonic trap (Fig 4) and the relative temperature $T' = T/T_{F0}$ was determined, where $k_B T_{F0} = h^2(6\pi^2 n_0)^{2/3}/2m$ is the Fermi energy of the non-interacting Fermi gas which has the same density distribution in the outer region as the majority cloud ($n_0$ is the central density of the non-interacting Fermi gas at zero temperature). We verified that anharmonicity of the trapping potential does not affect the fitted temperature (see appendix).

**Phase diagram for a homogeneous system**

The critical lines of the phase diagram of a homogeneous spin-polarized Fermi gas were obtained by determining the local temperature and spin polarization at the phase boundary. The local relative temperature $T_{loc} = T/T_{F1}$ was derived from the local density $n_1(R_c)$ as $T'(R_c) = T/T_{F0} \times (n_0/n_1(R_c))^{2/3}$. Since we observe no jump in the majority density within our resolution, $T_{F1}$ is well-defined at the phase boundary. The critical spin polarizations $\sigma_c$ and $\sigma_s$ were measured as $\sigma_c = \sigma(R_c)$ and $\sigma_s = \sigma(R_c - 0.05R_t)$ [37]. The discontinuity in the spin polarization profile implies that there is a thermodynamically unstable window, $\sigma_s < \sigma < \sigma_c$, leading to a first-order superfluid-to-normal phase transition. As the temperature increases, the unstable region reduces with $\sigma_c$ decreasing and $\sigma_s$ increasing. For high temperature when the bimodal feature in the spin polarization profile disappears, we recorded the condensate fraction as an indicator of superfluidity, using the rapid field-ramp technique [17]. As the temperature decreases, the condensate fraction gradually increases with a finite central polarization [19]. Such a smooth variation of the density profile and condensate fraction across the phase transition are characteristic of a second-order phase transition.

The phase diagram is characterized by the three distinguished points: the critical temperature $T_c$ for a balanced mixture, the critical spin polarization $\sigma_{c0}$ of a normal gas at zero temperature, and the tricritical point $(\sigma_{tc}, T_{tc})$ where the nature of the phase transition changes from second-order to first-order. Due to the lack of a predicted functional form for the phase transition line in the $\sigma$-$T$ plane, we apply a linear fit to the measured critical points, suggesting $T_{c0}/T_{F1} \approx 0.15$, $\sigma_{c0} \approx 0.36$ and $(\sigma_{tc}, T_{tc}/T_{F1}) \approx (0.20, 0.07)$. The value for $\sigma_{c0}$ agrees well with the prediction of QMC calculation of 0.39 [10]. The extrapolation of the phase diagram to $\sigma = 0$ is only tentative, since the in situ thermometry could not be applied to small population imbalances due to the narrowness of the non-interacting outer region. It is possible that the first- and second-order transition lines meet at the tricritical point with different slopes, similar to the case of liquid $^3$He-$^4$He mixtures [26].

The zero-temperature phase diagram and in particular the value for the CC limit are significantly affected by strong interactions in the normal phase. The CC limit reflects the energetic competition between a superfluid state and a partially-polarized normal state. When the chemical potential difference $\delta \mu = \mu_+ - \mu_-$ is larger than a critical difference $2h_c$, the normal state is energetically favorable and the superfluid state breaks down. In BCS theory, valid for weak interactions, the critical difference is $h_c = \Delta/\sqrt{2}$ [38] ($\Delta$ is the pairing gap). At unitarity, QMC studies predict $h_c = 1.00(5)\Delta(\approx 1.2\mu)$ [11] with the assumption of a non-interacting normal gas. Here, $\mu = (\mu_+ + \mu_-)/2$. The condition $\mu_{tc} = \mu - h_c < 0$ implies that $n_{tc} = 0$ in a non-interacting normal gas, and consequently $\sigma_{c0} = 100\%$, i.e., the absence of a partially-polarized normal phase. Mean-field approaches [12, 13, 14, 15, 16], which cannot treat the in-
FIG. 5: $\sigma$-$T$ phase diagram for a homogeneous spin-polarized Fermi gas with resonant interactions. The critical polarizations $\sigma_c$ (black solid circles and square) and $\sigma_s$ (gray solid circles) are displayed along the local $T/T_F$ at the phase boundary. The yellow area ($\sigma_s < \sigma < \sigma_c$) represents a thermodynamically unstable region, leading to the phase separation. Above the tricritical point, the phase transition in the center of the cloud was observed by the onset of pair condensation. For this, a cloud was evaporatively cooled, until it crossed the phase transition on a trajectory almost perpendicular to the phase transition line (see appendix). The critical spin polarization and temperature were obtained by interpolating between points without and with small condensates (black solid square). The linear fit to the $\sigma_c$’s is shown as a guide to the eye for the normal-to-superfluid phase transition line. Each data point consists of five independent measurements and error bars indicate standard deviation. The blue open symbols show theoretical predictions for the critical temperature of a homogeneous equal mixture ($\uparrow$: Bulgac et al. [7], $\triangle$: Burovski et al. [8], $\diamond$: Hausmann et al. [9]) and the critical polarization at zero temperature ($\diamond$: Lobo et al. [10]). The blue solid square is the measured critical temperature from Luo et al. [22], multiplied by $\sqrt{\xi}$ with $\xi = 0.42$ [11] to obtain local $T/T_F$ at the center. Finite temperature correction may increase the effective value of $\xi$.

interactions in the normal phase in an accurate way, also predict a high critical imbalance $\sigma_{c0} > 90\%$. Strong interactions between the atoms in the normal phase, however, have been observed through the compressed shape of the minority cloud [18] and the shift in the RF excitation spectrum [27]. The data in Figure 5 clearly establish a zero-temperature CC limit for $\sigma_{c0}$ in the range of 30% to 40%.

The density profiles at our lowest temperature provide quantitative information on the zero-temperature thermodynamics [23–29]. At zero temperature, the global chemical potential of a fully-paired superfluid in the core is given as $\mu_{s0} = \xi \varepsilon_F = \xi \hbar^2 (6\pi^2 n_{s0})^{2/3}/2m$

where $\varepsilon_F$ is the local Fermi energy and $n_{s0}$ is the majority (or minority) density at the center, whereas $\mu_{10} = \hbar^2 (6\pi^2 n_{0})^{2/3}/2m$ and $\mu_{01} = \eta_0 \mu_{10}$. From the thermodynamic equilibrium condition $\mu_{s0} = (\mu_{10} + \mu_{01})/2$, we obtain the chemical potential ratio as

$$\eta(r) = \frac{\eta_0 - r^2/R_c^2}{1 - r^2/R_c^2} = 2 \left( \frac{(n_{s0}/n_0)^{2/3} - 1}{1 - r^2/R_c^2} \right) + 1. \quad (1)$$

In our coldest sample ($\delta \approx 45\%$), the normalized central density and the radii for the phase boundary and the minority cloud were measured to be $n_{s0}/n_0 = 1.72(4), R_c/R_1 = 0.430(3)$, and $R_1/R_F = 0.728(8)$, respectively, yielding $\eta_c = \eta(R_c) \approx 0.03$ and $\eta_1 = \eta(R_1) \approx -0.69$ with $\xi = 0.42$ [11]. Furthermore, the critical difference is given as $h_c/\mu = (1 - \eta_c)/(1 + \eta_c) = 0.95$. Since theory clearly predicts $\mu < \Delta$ [9] [11], we have $h_c < \Delta$. If $h_c$ were larger than $\Delta$, polarized quasi-particles would have negative energies and form already at zero temperature. Therefore, up to our observed value of $h_c$, the fully-paired superfluid state is stable, and a polarized superfluid exists only at finite temperature.

The interface between two immiscible fluids involves a surface energy, leading to at least a small violation of the LDA. However, the observed sharp interface along the equipotential line and the flat top structure of the linear density difference profiles (Fig. 2d and e) imply that corrections to the LDA are smaller than the resolution of our experiment. These observations are inconsistent with the interpretations given for the experimental results reported in ref. [20, 21], where it has been shown that highly-elongated small samples are deformed by surface tension [30, 31]. The scaling of those surface effects to our parameters predicted a deviation of the aspect ratio of the superfluid core of $\approx 15\%$ from the trap aspect ratio [31], whereas we observe this deviation to be smaller than 2%. Note that surface tension would add energy in the phase-separated superfluid regime and would shift the CC limit to smaller values. Ref. [20, 21] concluded that the CC limit should be $\delta_0 > 95\%$ which is ruled out by our observations. We are not aware of any suggested effect which can reconcile the data of ref. [20, 21] with our phase diagram for a resonant superfluid. To identify this finite size effect and to fully understand the nature of the normal state [27] are still open questions for imbalanced Fermi gases.

**Conclusions**

We have established the phase diagram of a homogeneous spin-polarized Fermi gas with resonant interactions in the $\sigma$-$T$ plane. This includes the identification of a tricritical point where the critical lines for first-order and second-order phase transitions meet, and the final confirmation of a zero-temperature quantum phase transition, the CC limit of superfluidity, for a gas at unitarity. So far, predicted exotic superfluid states such as the breached-pair state in a stronger coupling regime ("BEC side") [13] [32]...
and the FFLO state in a weaker coupling regime (“BCS side”) have not been observed, but the novel methods of tomography and thermometry will be important tools in the search for those states.

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APPENDIX

Experimental details

The experimental procedure has been described in previous publications [17, 18, 19]. A degenerate Fermi gas of $^6$Li atoms was first prepared in an optical trap, using laser cooling and sympathetic cooling with $^{23}$Na atoms. A variable spin mixture of the two lowest hyperfine states $|\uparrow\rangle$ and $|\downarrow\rangle$ (corresponding to the $|F=1/2, m_F=1/2\rangle$ and $|F=1/2, m_F=-1/2\rangle$ states at low magnetic field) was created at a magnetic field $B = 885$ G. The final evaporative cooling by lowering the trap depth and all measurements were performed at $B = 833$ G. The temperature of the cloud was controlled by the lowest value of the trap depth in the evaporative cooling process. The axial trap frequency was $f_z = 23$ Hz. The two transverse trap frequencies are equal within less than 2%.

The optical signal in the phase-contrast imaging is proportional to the net phase shift of the imaging beam passing through a Fermi mixture, i.e. $c_1 n_\uparrow - c_\downarrow n_\downarrow \propto n_\uparrow / (\nu - \nu_\uparrow^0) + n_\downarrow / (\nu - \nu_\downarrow^0)$, where $\nu$ is the probe frequency of the imaging beam, and $\nu_\uparrow^0$ and $\nu_\downarrow^0$ are the resonance frequencies of the optical transition for the states $|\uparrow\rangle$ and $|\downarrow\rangle$, respectively. When the probe beam is tuned to the middle of the two transitions, i.e. $\nu = \nu_0 = (\nu_\uparrow^0 + \nu_\downarrow^0) / 2$, the optical signal reflects the density difference $\delta n = n_\uparrow - n_\downarrow$ with $c_\uparrow = c_\downarrow$. In our experiment, two phase-contrast images of the same sample were taken consecutively with different probe frequencies, $\nu_0_1$ and $\nu_0_2$. The two images record the density difference $n_{\uparrow 1} - n_{\downarrow 1}$ and the weighted density difference $n_{\downarrow 2} = \alpha_\uparrow n_\uparrow - \alpha_\downarrow n_\downarrow$. $n_\uparrow$ was determined by zeroing the optical signal with an equal mixture and $\alpha_\downarrow$ was determined by the signal ratio between the first and the second image for a highly imbalanced Fermi mixture with $|\delta| > 95\%$ (an almost fully polarized gas). Finally, we obtained $n_\uparrow = (\alpha_\downarrow n_{\uparrow 2} - n_{\downarrow 2}) / (\alpha_\downarrow - \alpha_\uparrow)$ and $n_\downarrow = (\alpha_\uparrow n_{\downarrow 2} - n_{\uparrow 2}) / (\alpha_\downarrow - \alpha_\uparrow)$. The difference between $\nu_0_1$ and $\nu_0_2$ was chosen to lie between 8 and 13 MHz. The time interval between the two images was 10 $\mu$s, and the pulse duration of each probe beam was 15 $\mu$s. Because the probe beam was off-resonant, no heating effect of the first pulse was observed in the second image.

Low-noise profiles were obtained by averaging the column density distribution of phase-contrast images along elliptical equipotential lines ($\lambda^2 x^2 + z^2 = r^2$). For the measurement of the critical spin polarization, the averaging region was restricted to $|x| < 12$ $\mu$m in order to preserve the sharp features at the phase boundary. The diffraction limit for our imaging system was about 2 $\mu$m. For the determination of local quantities in the profiles, we averaged over $\pm 5$ $\mu$m around a given position. For temperature determination, the averaging region was restricted to an axial sector of $\pm 60^\circ$ to avoid corrections due to radial anharmonicities (see appendix). The relative temperature $T'$ is determined as $T' \equiv T / TF_0 = (-6L_{\lambda_{\delta}}(-\zeta))^{-1/3}$, where $\zeta$ is the fugacity obtained from the fit $L_{\lambda_{\delta}}(z) \equiv \sum_{k=1}^{\infty} z^k / k^s$ is the Poly-Logarithmic function of order $s$.

Thermometry of ultracold Fermi gases

In our previous work [18, 19], temperatures have been determined by fitting the spatial wings of the majority component after expansion. However, we found that one can neglect collisions with the minority atoms in the core only for large population imbalances. In a simplified picture, one can regard collisions with the inner core as collisions with a moving wall, which moves outward radially and inward axially (due to the magnetic trapping potential). This results in different average kinetic energies (transversely and axially) of the free majority atoms in the outer region. Figure 7 shows the density distribution of the majority and minority components after expansion. Although the temperature has been overestimated by only 20% for typical experimental conditions
The absorption images of (a, d) the majority and (b, e) minority components were taken along (a, b) the axial $z$ and (d, e) transverse $y$ directions after expansion. (c) The azimuthally averaged column density profiles of the majority (red) and the minority (blue) cloud are obtained from (a) and (b), respectively. The excess majority atoms in the outer region interact with the core during expansion. The contour lines of the outer part of the majority cloud (color inset) are not elliptical and have the shape of a horse-track. This shows that the minority cloud pushes the outer majority atoms in the transverse direction, which is also indicated by the hump of the majority profile at the edge of the minority cloud. The population imbalance was $\delta \approx 55\%$.

If $\delta \approx 60\%$ in refs [18, 19], we do not regard this technique as well-calibrated absolute thermometry.

One other concept for thermometry determines temperature as the derivative of entropy with energy. So far, this concept could be implemented only for balanced fermion mixtures with certain approximations, and due to the need of determining a derivative, could only be used to obtain temperatures averaged over a certain range [22].

### Anharmonicity of the trapping potential

For the determination of temperatures from the spatial in situ profiles it was necessary to address the anharmonicity of the trapping potential. Our trap is generated by a weakly focused (beam waist $w \approx 125 \mu m$) infrared Gaussian laser beam (wavelength 1064 nm) near the saddle point of a magnetic potential. The total trapping potential is given as

$$V(\rho, z) = U_0 \exp\left(\frac{-2\rho^2}{w^2}\right) + \frac{m(2\pi f_z)^2}{2}\left(\frac{\rho^2}{2} + z^2\right),$$

where $\rho^2 = x^2 + y^2$. Note that gravity has been compensated by a magnetic field gradient. The axial confinement comes mainly from the magnetic potential with oscillation frequency of $f_z = 23$ Hz. The transverse magnetic potential is anti-trapping and limits the trap depth as

$$U = \frac{1}{4} m(2\pi f_\rho)^2 w^2 (1 - \frac{f_z^2}{2f_\rho^2}) \ln\left(\frac{2f_\rho^2 + f_z^2}{f_z^2}\right).$$

where $f_\rho$ is the transverse oscillation frequency in the central harmonic region. When the trap depth is comparable to the Fermi energy of a sample, the transverse anharmonicity will affect the shape of the cloud. Although in our experiments, the inner core and the outer cloud had the same aspect ratio as the trapping potential, indicating the absence of anharmonic effects, anharmonicities were not negligible in the spatial wings used to determine the temperature.

This issue was addressed by adjusting the angular averaging region (Fig. 8). Since the trapping potential is only anharmonic for large $\rho$, we could reduce the effect by decreasing the angle of the averaging sector around the $z$ direction. Both the experimental data and an exact simulation for an ideal Fermi gas show that the fitted temperature remains almost constant up to a certain angle and then increases when the averaging sector includes more of the transversely outer region. In our temperature determination, we chose the averaging sector to be $\pm 60^\circ$ which was large enough to create low-noise profiles, but kept the effect of the anharmonicities to below 10%. The 1D fit to angularly averaged profiles was computationally more efficient than a 2D fit to a selected region of the image. In a 2D fit, one could also include anharmonic terms in the fitting function.

### Polarized superfluid at finite temperature

When the two spin components have a chemical potential difference $2\hbar$, the BCS-type superfluid has two branches of quasiparticles with excitation energies $\sqrt{(\epsilon_k - \mu)^2 + \Delta^2} \pm \hbar$ where $\epsilon_k = \hbar^2 k^2/2m$. At finite temperature, the superfluid is polarized due to the large
thermal population of the lower branch compared to the upper branch. An interesting situation arises when $h$ becomes larger than $\Delta$, i.e. the lower branch has negative energy quasiparticles, implying that even at zero temperature the superfluid state would have a finite polarization. Our experiments show $h_\text{c} < \Delta$ at very low temperature, suggesting that a polarized superfluid state exists only at finite temperature. The breached-pair state with $h_\text{c} > \Delta$ at zero temperature has been predicted in a stronger coupling region (on the BEC side of the Feshbach resonance). Since $\Delta$ gradually decreases with higher temperature, it might be possible to have $h_\text{c} > \Delta$ at finite temperature, at least in the weakly-interacting BCS limit where $\Delta$ smoothly approaches zero at a second order phase transition point. One interesting problem is identifying this gapless region of $h > \Delta$ in the phase diagram for various coupling regimes.

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