Observation of Phase Separation in a Strongly-Interacting Imbalanced Fermi Gas

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We have observed phase separation between the superfluid and the normal component in a strongly interacting Fermi gas with imbalanced spin populations. The in situ distribution of the density difference between two trapped spin components is obtained using phase-contrast imaging and 3D image reconstruction. A shell structure is clearly identified where the superfluid region of equal densities is surrounded by a normal gas of unequal densities. The phase transition induces a dramatic change in the density profiles as excess fermions start being expelled from the superfluid.

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Cooper pairing is the underlying mechanism for the Bardeen-Cooper-Schrieffer (BCS) superfluid state of an equal mixture of two fermionic gases. An interesting situation arises when the two components have unequal populations. Does the imbalance quench superfluidity, does it lead to phase separation between a balanced and imbalanced region, or does it give rise to new forms of superfluidity? A search for exotic superfluid states is promising in imbalanced mixtures, since the imbalance destabilizes BCS-type s-wave pairing which is usually the strongest pairing mechanism [1, 2, 3, 4]. Recently, this problem has been experimentally addressed in ultracold atomic Fermi clouds with controlled population imbalance [5, 6, 7, 8]. Superfluidity was observed in a strongly interacting regime with a broad range of imbalances and the Pauli or Clogston limit of superfluidity [9, 10, 11] was characterized [5, 7].

The phase separation scenario suggests that unpaired fermions are spatially separated from a BCS-superfluid of equal densities due to the pairing gap in the superfluid region [12, 13]. In our previous experiments [5, 7, 8], we observed a strong central depletion in the difference profiles of expanding clouds indicating that excess atoms are expelled from the superfluid region. Ref. [5] reports depletion of excess atoms at the trap center. It has been clarified [12, 13] that none of these experiments answered the question: whether the densities of the two spin components are equal in the superfluid region and whether phase separation or rather distortions of the cloud due to interactions have occurred.

Here we report the direct observation of phase separation between the superfluid and the normal region in a strongly interacting Fermi gas with imbalanced spin populations. The density difference between the two spin components is directly measured in situ using a special phase-contrast imaging technique and 3D image reconstruction. We clearly identify a shell structure in an imbalanced Fermi gas where the superfluid region of equal densities is surrounded by a normal gas of unequal densities. This phase separation is observed throughout the strongly interacting regime near a Feshbach resonance.

Furthermore, we characterize the normal-to-superfluid phase transition of an imbalanced Fermi mixture using in situ phase-contrast imaging. The onset of superfluidity induces a dramatic change in the density profiles as excess fermions are expelled from the superfluid.

A degenerate Fermi gas of spin-polarized $^6\text{Li}$ atoms was prepared in an optical trap after laser cooling and sympathetic cooling with sodium atoms [14, 15]. The population imbalance $\delta$ of the two lowest hyperfine states $|1\rangle$ and $|2\rangle$ was adjusted with a radio-frequency sweep [5]. Here, $\delta = (N_1 - N_2)/(N_1 + N_2)$, where $N_1$ and $N_2$ are the atom numbers in $|1\rangle$ and $|2\rangle$, respectively. Interactions between these two states were strongly enhanced near a broad Feshbach resonance at $B_0 = 834$ G. The final evaporative cooling was performed at $B = 780$ G by lowering the trap depth. Subsequently, the interaction strength was adiabatically changed to a target value by adjusting the value of the magnetic-bias field $B$ with a ramp speed of $\leq 0.4$ G/ms. For typical conditions, the total atom number was $N_t = N_1 + N_2 \approx 1 \times 10^5$ and the radial (axial) trap frequency was $f_r = 130$ Hz ($f_z = 23$ Hz).

The condensate fraction in the imbalanced Fermi

![Phase-contrast imaging of the density difference of two spin states. (a) The probe beam is tuned to the red for the $|1\rangle \rightarrow |e\rangle$ transition and to the blue for the $|2\rangle \rightarrow |e\rangle$ transition. The resulting optical signal in the phase-contrast image is proportional to the density difference $n_e \equiv n_1 - n_2$, where $n_1$ and $n_2$ are the densities of the states $|1\rangle$ and $|2\rangle$, respectively. (b) Phase-contrast images of trapped atomic clouds in state $|1\rangle$ (left) and state $|2\rangle$ (right), and of an equal mixture of the two states (middle).]
The density difference between the two components was directly measured using a phase-contrast imaging technique \[18\]. Immediately after turning off the trap, the magnetic field was quickly ramped to \(B = 690\) G (1/\(k_F a\) \(\approx\) 2.6, where \(k_F\) is defined as the Fermi momentum of a non-interacting equal mixture with the same total atom number and \(a\) is the scattering length) in approximately 130 \(\mu\)s. The density profile of the expanding minority cloud was fit by a Gaussian for normal components (thermal molecules and unpaired atoms) and a Thomas-Fermi (TF) profile for the condensate \[18\].

The density difference between the two components was directly measured using a phase-contrast imaging technique described in Fig. 1. In this imaging scheme, the signs of the phase shifts due to the presence of atoms in each state are opposite so that the resulting phase signal is proportional to the density difference of the two states if the probe frequency is adjusted properly \[19\]. This technique allows us to directly image the in situ distribution of the density difference \(n_d(\vec{r})\) between the two components and avoid the shortcoming of previous studies \[14, 15\] where two images were subtracted from each other.

For a partially superfluid imbalanced mixture, a shell structure was observed in the in situ phase-contrast images (Fig. 2). Since the image shows the column density difference (the 3D density difference integrated along the \(y\)-direction of the imaging beam), the observed depletion in the center indicates a 3D shell structure with even stronger depletion in the central region. The size of this inner core decreases for increasing imbalance and the core shows a distinctive boundary until it disappears for large imbalance. We observe this shell structure even for very small imbalances, down to 5(3)\%, which excludes a homogeneous superfluid state at this low imbalance, contrary to the conclusions in Ref. \[15\].

The reconstructed 3D profile of the density difference shows that the two components in the core region have equal densities. We reconstruct 3D profiles from the 2D distributions \(n_d(\vec{r})\) of the column density difference using the inverse Abel transformation (Fig. 3) \[20\]. The only assumption employed in this process is that of cylindrical symmetry of our trap along the axial \(z\)-direction. The two transverse trap frequencies are equal to better than 2\% \[15\]. The reconstruction does not depend on the validity of the local density approximation (LDA) or a harmonic approximation for the trapping potential \[12, 21, 22\]. A 1D profile obtained by integrating \(n_d\) along the axial \(z\)-direction (Fig. 3(d)) shows a flat top distribution, which is the expected outcome for a shell structure with an empty inner region in a harmonic trap and assuming LDA.

The presence of a core region with equal densities for the two components was correlated with the presence of a pair condensate. The density difference at the center \(n_{d0}\) along with the condensate fraction is shown as a function of the population imbalance \(\delta\) in Fig. 4. As shown, there is a critical imbalance \(\delta_c\) where superfluidity breaks down due to large imbalance \[16, 17\]. In the superfluid region, i.e., \(\delta < \delta_c\), \(n_{d0}\) vanishes, and for \(\delta > \delta_c\), \(n_{d0}\) rapidly increases with a sudden jump around \(\delta \approx \delta_c\). We observe a similar behavior throughout the strongly interacting regime near the Feshbach resonance, \(-0.4 < 1/k_F a < 0.6\). This observation clearly demon-
and the “visibility” of the core region $\alpha$ strongly interacting regime at our coldest temperatures. This will be a subject of future research.

Larkin-Ovchinnikov (FFLO) state \[23, 24, 25\]. This will demonstrate that for this range of interactions a paired superfluid is spatially separated from a normal component of unequal densities.

The shell structure is characterized by the radius of the majority component, the radial position $R_p$ of the peak in $n_d(\vec{r})$, the size $R_c$ of the region where $n_d$ is depleted, and the “visibility” of the core region $\alpha \equiv (n_d(R_p) - n_{d0})/(n_d(R_p) + n_{d0})$ (Fig. 5). The sudden drop of $\alpha$ around $\delta \approx \delta_c$ has the same origin as the observed sudden jump of $n_{d0}$: the breakdown of superfluidity (compare Fig. 4). The comparison between $R_p$ and $R_c$ shows that the boundary layer between the superfluid and normal region is rather thin. It has been suggested that the detailed shape of profiles in the intermediate region could be used to identify exotic states such as the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state \[23, 24, 27\]. This will be a subject of future research.

The superfluid requires equal central densities in the strongly interacting regime at our coldest temperatures. A normal imbalanced Fermi mixture will have unequal densities. Thus, one should expect that a visible change in the density difference occurs as the temperature is lowered across the normal-to-superfluid phase transition \[7, 8\].

In situ phase-contrast images of a cloud at various temperatures are shown in Fig. 4. The temperature $T$ of the cloud is controlled with the final value of the trap depth in the evaporation process. The shell structure appears and becomes prominent when $T$ decreases below a certain critical value. This shell structure gives rise to the bimodal density profile of the minority component that we observed after expansion from the trap in our recent work \[7\]. Here we show via in situ measurements that the onset of superfluidity is accompanied by a pronounced change in the spatial density difference.

The phase transition is characterized in Fig. 4. As $T$ is lowered, $n_{d0}$ gradually decreases from its plateau value and the condensate fraction starts to increase. From the point of condensation (condensate fraction $> 1\%$) and deformation of the minority clouds ($\chi^2$ in Fig. 4(b)), we determine the critical temperature $T_c = 0.13(2) \ T_F$ for the imbalance of $\delta = 56(3)\%$. $T_F = 1.7 \ \mu K$ is the Fermi temperature of a non-interacting equal mixture with the same total atom number. The rise in $\chi^2$, the drop in $n_{d0}$ and the onset of condensation are all observed at about the same temperature. Better statistics are needed to address the question: whether some weak expulsion of
process. Phase-contrast images were taken after adiabatically ramping the trap depth up to $k_B \times 3.7 \, \mu K \,(f_r = 192 \text{ Hz})$. The whole evaporation and imaging process were performed at $B = 834 \, G \,(N_2 \approx 1.7 \times 10^7, \delta \approx 56\% )$. The field of view for each image is $160 \, \mu m \times 940 \, \mu m$. The vertical and horizontal scale of the images differ by a factor of 1.5.

FIG. 6: Emergence of phase separation in an imbalanced Fermi gas. The temperature of the cloud was controlled by varying the final value of the trap depth $U_f$ in the evaporation process. Phase-contrast images were taken after adiabatically ramping the trap depth up to $k_B \times 3.7 \, \mu K \,(f_r = 192 \text{ Hz})$. The whole evaporation and imaging process were performed at $B = 834 \, G \,(N_2 \approx 1.7 \times 10^7, \delta \approx 56\% )$. The field of view for each image is $160 \, \mu m \times 940 \, \mu m$. The vertical and horizontal scale of the images differ by a factor of 1.5.

FIG. 7: (Color online) Phase transition in an imbalanced Fermi gas. The phase transition shown in Fig. 6 was characterized by measuring (a) population imbalance $\delta$, (b) temperature $T$ (black circle), $\chi^2$ for fitting the minority cloud with a finite temperature Fermi-Dirac distribution (red triangle), (c) central density difference $n_{d0}$ (black circle), and condensate fraction (red triangle). The solid line is a guide to the eye for $\chi^2$. When $U_f < k_B \times 1 \, \mu K$, $\delta$ decreased mainly due to loss of the majority component. The number of the minority component was constant ($N_2 \approx 3.7 \times 10^8$). $T$ was determined from the non-interacting outer region of the majority cloud after 10 ms of ballistic expansion $T$ and $n_{d0}$ were averaged values of three independent measurements. The open (solid) arrow in (c) indicates the position for $T_c \,(T^*)$. See the text for the definitions of $T_c$ and $T^*$. Below a certain temperature $T^*$, $n_{d0}$ reaches zero while the condensate fraction is still increasing, implying that the superfluid region of equal densities continues to expand spatially with decreasing $T$. Full phase separation does not occur until this temperature $T^* < T_c$ is reached. We interpret the state between $T^*$ and $T_c$ as a superfluid of pairs coexisting with polarized quasi-particle excitations. This is expected, since at finite temperatures the BCS state of an equal mixture can accommodate excess atoms as fermionic quasi-particle excitations [23,20]. There is a finite energy given by the pairing gap $\Delta(T)$ for those quasi-particles to exist in the superfluid. The assumption that excess atoms should have thermal energy $k_B T > \Delta(T)$ to penetrate the superfluid region suggests the relation between $T^*$ and $\Delta(T)$ to be $k_B T^* \approx \Delta(T^*)$. From our experimental results, $T^* \approx 0.09 \, T_F$ and $\Delta(T^*) \approx \hbar \times 3.3 \, kHz$.

In conclusion, we have observed phase separation of the superfluid and the normal component in a strongly-interacting imbalanced Fermi gas. The shell structure consisting of a superfluid core of equal densities surrounded by a normal component of unequal densities was clearly identified using in situ phase-contrast imaging and 3D image reconstruction. The phase-contrast imaging technique combined with the 3D reconstruction process provides a new method to measure the in situ density distribution, allowing direct comparison with theoretical predictions.

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in order to compensate the effect of absorption, zeroing the optical signal in an equal mixture (Fig. 1).

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