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Homogeneous Atomic Fermi Gases

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We report on the creation of homogeneous Fermi gases of ultracold atoms in a uniform potential. In the momentum distribution of a spin-polarized gas, we observe the emergence of the Fermi surface and the saturated occupation of one particle per momentum state: the striking consequence of Pauli blocking in momentum space for a degenerate gas. Cooling a spin-balanced Fermi gas at unitarity, we create homogeneous superfluids and observe spatially uniform pair condensates. For thermodynamic measurements, we introduce a hybrid potential that is harmonic in one dimension and uniform in the other two. The spatially resolved compressibility reveals the superfluid transition in a spin-balanced Fermi gas, saturation in a fully polarized Fermi gas, and strong attraction in the polaronic regime of a partially polarized Fermi gas.

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Ninety years ago, Fermi derived the thermodynamics of a gas of particles obeying the Pauli exclusion principle [1]. The Fermi gas quickly became a ubiquitous paradigm in many-body physics; yet even today, Fermi gases in the presence of strong interactions pose severe challenges to our understanding. Ultracold atomic Fermi gases have emerged as a flexible platform for studying such strongly correlated fermionic systems [2–6]. In contrast to traditional solid state systems, quantum gases feature tunable spin polarization, dimensionality, and interaction strength. This enables the separation of quantum statistical effects from interaction-driven effects, and invites the exploration of rich phase diagrams, for example bulk Fermi gases in the BEC-BCS crossover [3–10] and Fermi-Hubbard models in optical lattices [11–20].

So far, Fermi gas experiments have been performed in inhomogeneous traps, where the nonuniform density leads to spatially varying energy and length scales. This poses a fundamental problem for studies of critical phenomena for which the correlation length diverges. Furthermore, in a gas with spatially varying density, a large region of the phase diagram is traversed, potentially obscuring exotic phases that are predicted to occur in a narrow range of parameters. This is most severe for supersolid states, such as the elusive FFLO state [21–23], where the emergent spatial period is well defined only in a homogeneous setting. A natural solution to these problems is the use of uniform potentials, which have recently proved to be advantageous for thermodynamic and coherence measurements with Bose gases [24–27].

Here, we realize homogeneous Fermi gases in a versatile uniform potential. For spin-polarized gases, we observe both the formation of the Fermi surface and the saturation at one fermion per momentum state, due to Pauli blocking. Spatially uniform pair condensates are observed for spin-balanced gases, offering strong prospects for the exploration of long-range coherence, critical fluctuations, and supersolidity.

In cases where the local density approximation (LDA) is valid, the spatially varying local chemical potential in an inhomogeneous trap can be utilized for thermodynamic [28–31] and spectroscopic [7,32,33] measurements. However, reconstructing the local density from line-of-sight integrated density profiles typically increases noise, while spatially selecting a central region of the gas reduces signal. A potential that is uniform along the line-of-sight is the natural solution. Combining the desirable features of homogeneous and spatially varying potentials, we introduce a hybrid potential that is uniform in two dimensions and harmonic in the third. The line-of-sight integration is now turned into an advantage: instead of averaging over a wide region of the phase diagram, the integration yields a higher signal-to-noise measurement of the local density. Using this geometry, we observe the characteristic saturation of isothermal compressibility in a spin-polarized gas, while a strongly interacting spin-balanced gas features a peak in the compressibility near the superfluid transition [31].

In our experiment, we prepare atoms in the two lowest hyperfine states of $^6$Li near a Feshbach resonance, and load them into the uniform potential of the optical box trap depicted in Fig. 1(a), after evaporative precooling in a crossed dipole trap. We typically achieve densities and Fermi energies of up to $n \approx 10^{12}$ cm$^{-3}$ and $E_F \approx h \times 13$ kHz, corresponding to $\sim 10^9$ atoms per spin state in the box. The lifetime of the
Fermi gas in the box trap is several tens of seconds. The uniform potential is tailored using blue-detuned laser light for the confining walls. The sharp radial trap barrier is provided by a ring beam generated by an axicon [34,35], while two light sheets act as end caps for the axial trapping [36]. Furthermore, the atoms are levitated against gravity by a magnetic saddle potential [3]. The residual radial anticonfining curvature of the magnetic potential is compensated optically, while an axial curvature results in a weak harmonic potential described by a trapping frequency of $\omega$ [47–50]. In contrast to conventional time of flight measurements, this method is unaffected by the in-trap size of the gas. The measured integrated density profile $n_{1D}(z)$ reflects the integrated momentum distribution $f_{1D}(k_z)$ via

$$f_{1D}(k_z) = \frac{2\pi\hbar}{V m \omega_z} n_{1D}(z).$$

Here, $V$ is the volume of the uniform trap. Figure 2(a) shows the integrated momentum distribution for different temperatures. Assuming a spherically symmetric momentum distribution, $f_k = f(k) = f(k)$. Noting that

$$f_{1D}(k_z) = \frac{1}{2\pi^2} \int dk_x dk_y f(k_x, k_y, k_z),$$

the three-dimensional momentum distribution can be obtained from the integrated momentum distribution by differentiation:

$$f_k = -4\pi \frac{df_{1D}(k_z)}{dk_z^2}.$$
As the temperature is lowered, the momentum distribution develops a Fermi surface, and we observe a momentum state occupation of 1.04(15) at low momenta [see Figs. 2(b)–2(d)], where the error in $f_k$ is dominated by the systematic uncertainties in the box volume and the imaging magnification [36]. This is the direct consequence of Pauli blocking and confirms saturation at one fermion per momentum state.

An important motivation for the realization of a homogeneous Fermi gas is the prospect of observing exotic strongly correlated states predicted to exist in narrow parts of the phase diagram, such as the FFLO state [21,22]. In a harmonic trap, such states would be confined to thin isopotential shells of the cloud, making them challenging to observe. We observe pair condensation in a uniformly trapped strongly interacting spin-balanced Fermi gas through a rapid ramp of the magnetic field during time of flight [3,51,52], as shown in Figs. 3(a)–3(c). The pair condensate at the end of the ramp barely expands in time of flight. As a result, the in-trap homogeneity is reflected in a flat top profile of the condensate [see Fig. 3(f)].

Although a fully uniform potential is ideal for measurements that require translational symmetry, a spatially varying potential can access a large region of the phase diagram in a single experimental run. To harness the advantages of both potentials, we introduce a hybrid geometry that combines the radially uniform cylinder trap with an axially harmonic magnetic trap along the $z$ direction [see Fig. 4(a)]. As a benchmark for the hybrid trap, we perform a thermodynamic study of both a strongly spin-imbalanced and a spin-balanced unitary gas. Figures 4(c)–4(e) display for both cases the $y$-axis averaged local density, temperature, and compressibility. The data shown in Fig. 4 are extracted from an average of just six images per spin component. For comparison, precision measurements of the equation of state at unitarity, performed in conventional harmonic traps, required averaging of over 100 absorption images [31]. The temperature is obtained from fits to the known equations of state of the noninteracting and spin-balanced unitary Fermi gas, respectively. From the local density in the hybrid trap, we determine the normalized isothermal compressibility $\tilde{\kappa} = \kappa/\kappa_0 = -\partial E_F/\partial U|_T$ for the spin-imbalanced and the spin-balanced gas. Here, $U$ is the external potential, and $\kappa_0 = 1/(1/nEF)$ is the compressibility of the noninteracting Fermi gas at zero temperature [31].

The strongly spin-imbalanced cloud features two distinct regions in the trap. The center of the cloud is a partially polarized region in which $(n_\uparrow - n_\downarrow)/(n_\uparrow + n_\downarrow) > 0.64$, well above the Clogston-Chandrasekhar limit of superfluidity [53–55]. Surrounding the center is a fully polarized region, where the compressibility is seen to saturate: the real space consequence of the Pauli blocking in momentum space demonstrated in Fig. 2.

The majority spin component in the partially polarized region is affected by the presence of the minority spin component. We measure the compressibility $\kappa_\uparrow = -\partial E_{F\uparrow}/\partial U$ in the partially polarized region, and observe an increase compared to the fully polarized gas. This is expected as...
the minority atoms in the center of the trap attract majority atoms and form polarons [7,8]. The effect is indeed predicted by the polaron equation of state [29,30,56]. The observation of this subtle effect highlights the sensitivity of the hybrid potential for thermodynamic measurements.

In the spin-balanced case, $\kappa/\kappa_0$ is significantly larger than for the ideal Fermi gas due to strong interactions. The two prominent peaks in the reduced compressibility signal the superfluid transition at the two boundary surfaces between the superfluid core and the surrounding normal fluid. Near the center of the trap, the reduced compressibility agrees with the $T = 0$ equation of state $\kappa/\kappa_0 = 1/\xi = 2.65(4)$, where $\xi$ is the Bertsch parameter. The shaded region in the right column of Fig. 4 shows the superfluid part of the gas, where the temperature is below the critical temperature for superfluidity $T_c = 0.177T_F$ [31].

The realization of uniform Fermi gases promises further insight into phases and states of matter that have eluded observation or quantitative understanding. This includes the observation of the quasiparticle jump [57] in the momentum distribution of a Fermi liquid, critical fluctuations in the BCS-BCS crossover, and long-lived solitons [58]. Of particular interest are spin imbalanced mixtures that have been studied extensively in harmonic traps [29,30,55,59–62], where the trap drives the separation of normal and superfluid phases into a shell structure. This phase separation should occur spontaneously in a uniform spin-imbalanced gas, possibly forming domains of superfluid and eventually ordering into an FFLO state. In addition, the hybrid potential is a valuable tool for precision measurements that rely on an in-trap density variation. For example, spatially resolved rf spectroscopy [32] in the hybrid potential would measure the homogenous response of the system over a large range of normalized temperatures $T/T_F$ in a single experimental run.

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