Probing local quantities in a strongly interacting Fermi gas

Yoav Sagi, Tara E. Drake, Rabin Paudel, Roman Chapurin and Deborah S. Jin

JILA, National Institute of Standards and Technology and the University of Colorado, and the Department of Physics, University of Colorado, Boulder, CO 80309-0440, USA

E-mail: jin@jilau1.colorado.edu

Abstract. The collective behavior of an ensemble of strongly interacting fermions is central to many physical systems, and its theoretical description is challenging due to the many-body nature of the problem. The ultracold Fermi gas is an ideal model system to shed light on this issue, as it provides excellent controllability, reproducibility, and unique detection methods. One of the problems, however, which complicates the interpretation of such experiments is the inherent density inhomogeneity of the gas due to harmonic confinement. We have developed a technique to overcome this difficulty by selectively probing atoms near the center of a trapped gas while still retaining momentum resolution. In this contribution to the 21th International Conference on Laser Spectroscopy (ICOLS 2013), we give an overview of this technique and some of the observations that have resulted from its implementation.

1. Introduction

When a gas of fermions is cooled to a temperature \((T)\) lower than the Fermi temperature \((T_F)\), Fermi-Dirac statistics start to have an appreciable effect [1]. At \(T = 0\), a homogeneous gas of non-interacting fermions fills all available states in momentum space up to the Fermi surface. The sharpness of the transition from filled states to empty states (the Fermi step) is determined by \(T/T_F\). When the density of the gas is non-uniform in space but the variations are gradual enough (i.e. the local density approximation holds), then the different densities at each position give rise to different local \(T_F\). This is the case in all experiments where the atoms are trapped by some non-uniform external potential; in most cases, this potential is approximately harmonic. Since the cloud is in thermal equilibrium \((T\) is the same everywhere\), \(T/T_F\) will vary across the gas. Any physical quantity of interest which depends on the scaled temperature, \(Q(T/T_F)\), will also vary across the gas. A global measurement of that quantity will yield

\[
\bar{Q} = N^{-1} \int Q[T/T_F(r)] n(r) d^3r,
\]

where \(n(r)\) is the density distribution, and \(N\) is the total number of atoms. In general, it can be difficult to interpret the measured \(\bar{Q}\) and compare it directly to theoretical predictions. Moreover, this density-weighted averaging causes sharp features in \(Q(T/T_F)\) to wash-out and disappear in \(\bar{Q}\).

A prime example of such a sharp feature is the step in the momentum distribution of non-interacting fermions at low \(T/T_F\). In a harmonically trapped gas, the highest density, and
therefore also the lowest $T/T_F$, occurs in the center. The outskirts of the cloud are effectively at higher temperature (higher $T/T_F$), which means that the corresponding Fermi step is broader. When averaged together, the resulting momentum distribution of a trapped cloud does not exhibit a sharp transition and the location of the transition shifts. This situation is illustrated in figure 1.

**Figure 1. The wash-out of sharp features due to density inhomogeneity of a trapped gas.** The momentum distribution, $\Pi(k)$, of a homogeneous non-interacting Fermi gas (solid blue line) compared to that of a harmonically trapped gas (red dashed line), both at $T/T_F = 0.1$. In both cases, we normalize the distribution such that $\int \Pi(k) d^3k = 1$. The momentum is given in units of the Fermi momentum, $k_F$; either the trap $k_F$ for the trapped gas, given by $(2m/\hbar^2)(\omega_x \omega_y \omega_z 6N)^{1/6}$, or the homogeneous $k_F$, given by $(6\pi^2 n)^{1/3}$. Here, $m$ is the mass, $\omega_i$ is the oscillation frequency in the trap for axis $i$, $n$ and $N$ are the density and total number of atoms in one of the two interacting spin states, respectively.

For a strongly interacting Fermi gas, much attention has been devoted in the past to studies of the Fermi superfluid and the BCS-BEC crossover. At unitarity ($1/k_F a \rightarrow 0$, where $a$ is the scattering length), the transition temperature is around 0.2\(T_F\) [2]. Above this temperature, the gas is in the normal phase, the nature of which is still under debate. Some theories predict that pairing instability will persist into the normal phase at temperatures close to the phase transition, leading to a pseudogap phase [3, 4, 5, 6]. Experiments on a trapped gas using atoms photoemission spectroscopy (PES) have found evidence for the existence of this phase [2]. The range of temperatures at which a pseudogap phase is expected to exist is very limited [5], hence signatures of its existence are easily obscured by averaging over inhomogeneous density, which includes parts of the cloud with much higher $T/T_F$. As such, there is a need to obtain quantitative results on a strongly interacting Fermi gas with a temperature spread as small as possible.

The experiments described here were performed with an ultra-cold gas of $^{40}$K atoms [7, 8, 9]. The atoms are initially collected from a high temperature isotopically enriched source by a magneto-optical trap, after which they are pushed by a laser to a second chamber with a much lower residual pressure, where they are collected in a second magneto-optical trap. Evaporative cooling is performed initially in a magnetic trap, followed by evaporation in a crossed dipole trap. The evaporation ends with an equal mixture of the $|f, m_f\rangle = |9/2, -9/2\rangle$ and $|9/2, -7/2\rangle$ spin states, where $f$ is the quantum number denoting the total atomic spin and $m_f$ is its projection. The scattering length between these two states can be controlled by an applied magnetic field via the s-wave Fano-Feshbach resonance around 202 G. The final stage of the evaporation is done in a magnetic field of 203.4 G where the s-wave scattering length between the two spin states is about $-850a_0$, where $a_0$ is the Bohr radius. Typically, there are around 100000-250000 atoms...
per spin state. We detect the atoms using absorption imaging after a time of flight ranging between 3 ms to 16 ms.

2. The crossed hollow light beams technique

Ideally, a solution to the density inhomogeneity problem should do the following: reduce the spread of $T/T_F$ in the sample being probed, enable a measurement of the momentum distribution of the probed sample (e.g. PES can be performed), and not limit the range of achievable temperatures and densities. The latter requirement makes solutions based on modifying the trapping geometry challenging, since they may result in lower densities which makes the evaporation less efficient. However, much improvement has been reported recently in this route, where experiments have demonstrated the creation of a Bose-Einstein condensate in a quasi-uniform potential [10]. We have chosen not to alter the trapping geometry, but to post-select a small fraction of the atoms near the cloud center for interrogation [8]. In the local density approximation, a small volume of the gas behaves as a homogeneous system.

Probing atoms in a small volume is accomplished by intersecting two orthogonally propagating hollow light beams that optically pump atoms into a spin state that is dark to the detection. The spatial mode of the optical pumping beams is a second-order Laguerre-Gaussian, given by $I(r) = \frac{P}{\pi w^2} \left( \frac{2r^2}{w^2} \right)^2 e^{-\frac{2r^2}{w^2}}$, where $P$ is the total optical power and $w$ is the waist. The fraction of atoms probed can be changed by varying the intensity of these optical pumping beams. Usually, the two beams are aligned to the center of the cloud (i.e. where $T/T_F$ is lowest and the density is highest), but in principle, it is possible to probe any position in the cloud. It is important to keep in mind that the atoms which are not probed are not driven out of the trap, but only optically pumped to a dark state. The hollow light beams are turned on close to the time of the trap release, where initially the beam that propagates perpendicular to the long axis of the cloud is turned on for 10 $\mu$s followed by a 40 $\mu$s pulse of the second beam. These durations are much shorter than all relevant dynamical timescales in the experiment.

3. Experiments with a homogeneous Fermi gas

The full, step-like momentum distribution of a homogeneous gas of non-interacting fermions is shown in most statistical mechanics textbooks but has never been observed directly. The momentum distribution of a trapped gas of non-interacting fermions was measured before, and its shape is very well understood, albeit not displaying any sharp features [11]. In a first set of experiments, we used the hollow light beams technique to directly observe the Fermi surface [8]. In these experiments, the final magnetic field is set to 208.2 G, where the scattering length is approximately $-30 a_0$ ($a_0$ is the Bohr radius) and the gas is very weakly interacting with a dimensionless interaction strength of $1/k_F a \sim 91$. The hollow light beams are switched on immediately after the trap is switched off. Absorption images are taken after 10 ms or 12 ms of time-of-flight. The three-dimensional momentum distribution is obtained from the integrated two-dimensional image by applying an inverse Abel transform.

As can be seen in figure 2, as the intensity of the hollow light beams is increased, a momentum distribution with a sharp step gradually emerge. When the fraction of atoms probed is less than 30%, we find that the data fits very well to a homogeneous Fermi-Dirac distribution [8]. Moreover, from that fit we can extract the average $k_F$ and temperature of the gas, which correspond to the position and sharpness of the step. We find that sharpness of the Fermi step in our data at low probing fractions is limited by the temperature and not by the remaining density inhomogeneity.

In the regime of strong interactions, we have used the hollow light beam technique to measure Tan’s contact [9]. The contact has emerged in recent years as an important thermodynamic parameter for quantum gases that connects many seemingly unrelated quantities through a set
Figure 2. The emergence of the Fermi surface in a gas of non-interacting fermions. The normalized momentum distributions for the central 100%, 59%, and 23% of the trapped gas. The solid lines show fits to the expected momentum distribution for a homogeneous Fermi gas; we fix $T$ to the value determined for the trapped gas, leaving $k_F$ (and the corresponding $T_F$) as single fit parameter. The momentum is given in units of this $k_F$. This data was taken at approximately $T/T_{F,\text{trap}} = 0.12$.

of universal relations [12, 13, 14, 15, 16, 17]. Many of these relations were tested experimentally [18, 19, 20, 21]. The dependence of the contact on temperature was investigated in several theoretical works [22, 23, 24, 25, 26]. Interestingly, there are significant discrepancies in the predicted contact of a homogeneous system from different theories, especially in the vicinity of the superfluid phase transition. This makes the homogeneous contact a good benchmark for many-bodies theories. For a trapped gas, these discrepancies almost completely vanish because of averaging over different local $T/T_F$ [27].

We extract the contact from measurement of the rf line shape, which measures the probability that an rf pulse at some frequency transfers an atom from one of the two interacting spin states to a third weakly interacting state. A universal relation connects the high frequency tail of the line shape to the contact, $C$ (see Ref. [17] and references therein): $\frac{\Gamma(\nu)}{\int_{-\infty}^{\infty} \Gamma(\nu') d\nu'} = C' \left( Nk_F\sqrt{2\pi^2 \nu^{3/2}} \right)$ for $\nu \to \infty$, where $\nu$ is the rf detuning in units of $E_F/h$, ($E_F$ is the Fermi energy and $h$ is Planck’s constant). After cooling the gas, the magnetic field is ramped in 50 ms from 203.4 G to the Feshbach resonance at 202.2 G. The hollow light beams are turned on 280 $\mu$s
before trap release. The line shape is measured using a 100 µs long rf pulse with a gaussian field envelope with a width of 17 µs. This pulse is centered 180 µs before trap release. We set the rf power well below the value where we see the onset of saturation of the number of outcoupled atoms, such that the line shape is indeed measured in the linear response regime.

As with a trapped gas, the tail of the measured line shape of a homogeneous sample shows the expected scaling of $\nu^{-3/2}$, from which we extract the homogeneous contact [9]. We have found a gradual decrease of the contact when the temperature is increased, in good agreement with the virial expansion (which is expected to hold for $T/T_F \gtrsim 1$). We have also observed a sharp drop in the contact at a temperature consistent with the superfluid phase transition. Several theoretical works predict a narrow enhancement in the contact around the superfluid critical temperature, due to pair fluctuations [23]. However, we do not observe a such pronounced peak in the experiment.

Figure 3. PES measurement on a homogeneous unitary Fermi gas. The occupied spectral function, with and without applying the hollow light beams technique, of a unitary gas ($1/k_F a = 0$) at $T/T_c = 0.8$, where $T_c$ is the superfluid phase transition, determined using the molecular projection technique [28, 2]. The color at each energy and momentum is proportional to the probability to excite from the many-body state an atom with that particular energy and momentum (plotted in a logarithmic scale). As a comparison, the black solid line is the quadratic dispersion of a non-interacting particle.

A measurement technique that can probe the many-body state of the gas and provide information about the nature of the normal state is PES [7]. Atom PES measurement is achieved using momentum-resolved spectroscopy. Since the outcoupled atoms are weakly interacting, their energy-momentum dispersion is simply that of a free particles. Using this fact and energy and momentum conservation, it is possible to reconstruct the occupied spectral function of system, which gives the probability to find an atom at some energy and momentum [7]. As in the case of the measurement of the Fermi surface, at trap release we pulse the hollow light beams such that the spectral function is measured only for a small fraction of the gas at the cloud center.

An example of such a measurement is shown in figure 3, for a gas at $T/T_c = 0.8$, where $T_c$ is the superfluid critical temperature. The left panel shows the measured occupied spectral function of a trapped gas, while the right panel shows the result when we probe only the central 34% of the gas. Several observations can be made; much of the signal that has been removed from the left panel is close to the free-particle line. This is expected, since the atoms in the outskirts of the cloud are at much lower densities (and higher effective $T/T_F$), so the mean-field interaction energy shift is much smaller. Also, the widths of the energy distribution curves (EDC), which are vertical cuts through the data, are narrower for the more homogeneous sample on the right. We expect future homogeneous PES measurements at different interaction
strengths and temperatures in the BCS-BEC crossover to provide insight on the nature of the normal state.

4. Conclusion and outlook
The combination of both spatial and momentum resolution in the hollow light beams technique enable us to probe important quantities in a homogeneous sample. There is a tradeoff between how homogeneous the sample we probe is and the signal-to-noise ratio in our measurement, and we find that probing $\sim 30\%$ of the cloud seems to strike the right balance. We have presented here several measurements using the hollow light beams technique, both for weakly and strongly interacting fermions. Future projects include a thorough study of the homogeneous atom PES across the BCS-BEC crossover, and investigation of the spatial variance of the condensate fraction below the superfluid phase transition.

We would like to thank the JILA BEC group for fruitful discussions. We acknowledge funding from the NSF and NIST.

References
[1] DeMarco, B., Papp, S. B., and Jin, D. S. *Phys. Rev. Lett.* 86, 5409–5412 Jun (2001).
[2] Gaebler, J. P., Stewart, J. T., Drake, T. E., Jin, D. S., Perali, A., Pieri, P., and Strinati, G. C. *Nat. Phys.* 6(8), 569–573 August (2010).
[3] Chien, C.-C., Guo, H., He, Y., and Levin, K. *Phys. Rev. A* 81, 023622 Feb (2010).
[4] Hu, H., Liu, X.-J., Drummond, P. D., and Dong, H. *Phys. Rev. Lett.* 104, 240407 Jun (2010).
[5] Magierski, P., Wlazlowski, G., and Bulgac, A. *Phys. Rev. Lett.* 107, 145304 Sep (2011).
[6] Perali, A., Palestini, F., Pieri, P., Strinati, G. C., Stewart, J. T., Gaebler, J. P., Drake, T. E., and Jin, D. S. *Phys. Rev. Lett.* 106, 060402 Feb (2011).
[7] Stewart, J. T., Gaebler, J. P., and Jin, D. S. *Nature* 454(7205), 744–747 August (2008).
[8] Drut, J. E., Lähde, T. A., and Ten, T. *Phys. Rev. Lett.* 106, 020402 May (2013).
[9] Sagi, Y., Drake, T. E., Paudel, R., and Jin, D. S. *Phys. Rev. A* 86, 031601 Sep (2012).
[10] Gaunt, A. L., Schmidutz, T. F., Gotlibovych, I., Smith, R. P., and Hadzibabic, Z. *Phys. Rev. Lett.* 110, 200406 May (2013).
[11] Jin, D. S. and Regal, C. A. *Ultra-cold Fermi Gases*, volume 164 of *Proceedings of the International School of Physics "Enrico Fermi*", chapter Fermi Gas Experiments, 1–51. IOS Press (2007).
[12] Tan, S. *Ann. Phys.* 323, 2952–2970 (2008).
[13] Tan, S. *Ann. Phys.* 323, 2987–2990 (2008).
[14] Tan, S. *Ann. Phys.* 323, 2971–2986 (2008).
[15] Braaten, E., Kang, D., and Platter, L. *Phys. Rev. Lett.* 100, 205301 (2008).
[16] Zhang, S. and Leggett, A. J. *Phys. Rev. A* 79, 023601 (2009).
[17] Braaten, E. In *The BCS-BEC Crossover and the Unitary Fermi Gas*, Zwerger, W., editor, volume 836 of *Lecture Notes in Physics*, 193–231. Springer Berlin / Heidelberg (2012).
[18] Stewart, J. T., Gaebler, J. P., Drake, T. E., and Jin, D. S. *Phys. Rev. Lett.* 104, 235301 Jun (2010).
[19] Kuhnle, E. D., Hu, H., Liu, X.-J., Dyke, P., Mark, M., Drummond, P. D., Hannaford, P., and Vale, C. J. *Phys. Rev. Lett.* 105, 070402 Aug (2010).
[20] Partridge, G. B., Strecker, K. E., Kamar, R. I., Jack, M. W., and Hulet, R. G. *Phys. Rev. Lett.* 95, 020404 Jul (2005).
[21] Werner, F., Tarruell, L., and Castin, Y. *Eur. Phys. J. B* 68, 401–415 (2009).
[22] Yu, Z., Bruun, G. M., and Baym, G. *Phys. Rev. A* 80, 023615 Aug (2009).
[23] Palestini, F., Perali, A., Pieri, P., and Strinati, G. C. *Phys. Rev. A* 82, 021605 Aug (2010).
[24] Enss, T., Haussmann, R., and Zwerger, W. *Ann. Phys.* 326(3), 770 – 796 (2011).
[25] Hu, H., Liu, X.-J., and Drummond, P. D. *New J. Phys.* 13(3), 035007 (2011).
[26] Drut, J. E., Lähde, T. A., and Ten, T. *Phys. Rev. Lett.* 106, 205302 May (2011).
[27] Kuhnle, E. D., Hoinka, S., Dyke, P., Hu, H., Hannaford, P., and Vale, C. J. *Phys. Rev. Lett.* 106, 170402 Apr (2011).
[28] Regal, C. A., Greiner, M., and Jin, D. S. *Phys. Rev. Lett.* 92, 040403 Jan (2004).