Universal behavior of pair correlations in a strongly interacting Fermi gas

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We show that short-range pair correlations in a strongly interacting Fermi gas follow a simple universal law described by Tan's relations. This is achieved through measurements of the static structure factor which displays a universal scaling proportional to the ratio of Tan's contact to the momentum $\mathcal{C}/q$. Bragg spectroscopy of ultracold ^{6}Li atoms from a periodic optical potential is used to measure the structure factor for a wide range of momenta and interaction strengths, providing broad confirmation of this universal law. We calibrate our Bragg spectra using the f-sum rule, which is found to improve the accuracy of the structure factor measurement.

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Universality is a remarkable property of strongly interacting systems of fermions [1–3]. Universality means that all dilute Fermi systems with sufficiently strong interactions behave identically on a scale given by the average particle separation. With the discovery of universality in the Bose-Einstein condensate (BEC) to Bardeen-Cooper-Schrieffer (BCS) crossover, ultracold Fermi gases near Feshbach resonances have become a central topic in atomic physics [4–10]. Strongly interacting Fermi systems arise in a wide variety of settings, from astrophysical to nuclear and condensed matter systems. One can therefore study universality in ultracold atomic gases to help understand other strongly interacting Fermi superfluids, taking advantage of the ability to precisely control the atom-atom interactions.

Understanding these strongly interacting Fermi gases, however, poses significant challenges [11]. In 2005 Shina Tan made dramatic progress by deriving several exact relations for Fermi gases in the BEC-BCS crossover, which relate the microscopic properties to bulk thermodynamic quantities [12–14]. These exact relations are applicable in broad circumstances: zero or finite temperatures, superfluid or normal phases, homogeneous or trapped systems, and in few or many-body systems.

In this letter, we experimentally verify a universal relation for short-range pair correlations [12] using Bragg spectroscopy. This is achieved through measurements of the static structure factor, given by the Fourier transform of the pair correlation function [15]. The structure factor of a unitary Fermi gas has an exact scaling with the ratio of Tan's contact to the momentum $\mathcal{C}/q$. For systems with finite scattering length, we also confirm the first order correction to the universal law. Our measurements are compared to new calculations for the contact based on a recently developed below-threshold Gaussian pair fluctuation theory [16].

The contact $\mathcal{C}$ in a two component Fermi gas quantifies the likelihood of finding two fermions with opposite spin close enough to interact with each other. In systems where the range of the interaction potential is negligible, this single parameter encapsulates all of the information required to determine the many-body properties [17, 18]. $\mathcal{C}$ depends on the s-wave scattering length, density and temperature of the system. Tan showed that the internal energy of a gas across the BEC-BCS crossover can be expressed as a functional of the momentum distribution which has a $\mathcal{C}/q^4$ dependence at large momentum q and that the pair correlation function diverges as $\mathcal{C}/r^2$ at short distance $r < 1/k_F$, where k_F is the Fermi wavevector [12, 15]. Tan also derived the adiabatic relation $dE/d(-1/a) = \hbar^2\mathcal{C}/(4\pi m)$, where m is the atomic mass, giving the change in the total energy E due to an adiabatic change in the scattering length [13] and extended the virial theorem to finite a and imbalanced mixtures [14]. The contact $\mathcal{C}$ was first extracted [19] from the number of closed-channel molecules determined through photo-association [8] and the adiabatic and virial Tan relations were very recently verified experimentally [20]. We will generally refer to the dimensionless contact $\mathcal{I}$ given by $\mathcal{C}/(Nk_F)$ where N is the number of particles.

Short-range structure in a quantum fluid depends upon the relative wave-function of the interacting particles, in this case fermions in different spin states. In a two-component (spin-up/spin-down) Fermi gas with contact interactions this is given by $\psi_{\uparrow\downarrow}(r) \propto 1/r - 1/a$, where a is the s-wave scattering length. Starting from this wave-function, Tan showed that the spin-antiparallel pair correlation function is given by Eq. (1) which includes the contact as a pre-factor [12]

$$g^{(2)}_{\uparrow\downarrow}(r) \to \frac{\mathcal{I}}{16\pi^2}\left(\frac{1}{r^2} - \frac{2}{ar}\right). \quad (1)$$

Pair correlation functions are difficult to measure directly in ultracold gases; however, it is possible to measure macroscopic quantities which depend on correlation functions in a well defined way. A prime example is the static structure factor, $S(k)$, which is given by the Fourier transform of $g^{(2)}(r)$ ($q = \hbar k$ is the probe momentum). In