What Atomic Liquids Can Teach Us about Quark Liquids

Thomas Schäfer

Department of Physics, North Carolina State University, Raleigh, NC 27695, USA

We discuss some aspects of cold atomic Fermi gases in the unitarity limit that are of interest in connection with the physics of quark matter and the quark gluon plasma. We consider, in particular, the equation of state, transport properties, the critical temperature for pair condensation, and the response to a pair breaking stress.

§1. Introduction

Over the last ten years there has been truly remarkable progress in the study of cold, dilute gases of fermionic atoms in which the scattering length $a$ of the atoms can be controlled experimentally. These systems can be realized in the laboratory using Feshbach resonances, see Ref. 1) for a review. A small negative scattering length corresponds to a weak attractive interaction between the atoms. This case is known as the BCS (Bardeen-Cooper-Schrieffer) limit. As the strength of the interaction increases the scattering length becomes larger. It diverges at the point where a bound state is formed. The point $a = \infty$ is called the unitarity limit, because the scattering cross section saturates the $s$-wave unitarity bound $\sigma = 4\pi/k^2$. On the other side of the resonance the scattering length is positive. In the BEC (Bose-Einstein condensation) limit the interaction is strongly attractive and the fermions form deeply bound molecules.

The unitarity limit is of particular interest. In this limit the atoms form a strongly coupled quantum liquid which exhibits universal behavior. In the BCS limit the atomic gas is characterized by the small parameter $(k_Fa)$, where $k_F$ is the Fermi momentum. In the unitarity limit this parameter is infinite and the system is strongly coupled. Universality arises from the fact that short distance effects are suppressed by the small parameter $(k_Fr)$, where $r$ is the effective range. In the experiments performed to date $(k_Fr) \ll 1$, and we expect that the theoretical limit $(k_Fa) \to \infty$, $(k_Fr) \to 0$ is well defined. Dilute fermions in the unitarity limit provide an interesting model system in which a number of questions regarding the behavior of strongly coupled quantum liquids can be studied. In this contribution we shall study a number of issues that are of relevance to the phase diagram of QCD:

- What is the equation of state at strong coupling? Is the transition from weak to strong coupling smooth?
- What are the transport properties at strong coupling? Are transport properties more sensitive to the coupling than thermodynamic quantities? Do atomic liquids respect the proposed bound on the ratio of shear viscosity to entropy density?
- What is the critical temperature for pairing? Is there a universal upper bound
on $T_c/E_F$, where $T_c$ is the critical temperature and $E_F$ is the Fermi energy.

- How does the paired state below $T_c$ respond to a pair breaking stress? Are there any intermediate states that separate the fully paired state from the normal state?

§2. Equation of state

Asymptotic freedom implies that the equation of state of a quark gluon plasma at $T \gg \Lambda_{\text{QCD}}$ is that of a free gas of quarks and gluons. Numerical results from lattice QCD calculations show that at $T \sim 2T_c$, which is relevant to the early stages of heavy ion collisions at RHIC, the pressure and energy density reach about 85% of the free gas limit. This is consistent with the first order perturbative correction. Higher order terms in the perturbative expansion are very poorly convergent, but this problem can be addressed using resummation techniques.\footnote{In this framework the degrees of freedom are dressed quasi-quarks and quasi-gluons, and these quasi-particles are weakly interacting.}

Transport properties of the plasma indicate that this may not be correct. Experiments at RHIC indicate that the viscosity of the plasma is very small, and that the opacity for high energy jets is very large. An interesting perspective on this issue is provided by a strong coupling calculation performed in the large $N_c$ limit of $\mathcal{N} = 4$ SUSY Yang Mills theory. The calculation is based on the duality between the strongly coupled gauge theory and weakly coupled string theory on $\text{AdS}_5 \times S_5$ discovered by Maldacena.\footnote{The correspondence can be extended to finite temperature. In this case the relevant configurations is an $\text{AdS}_5$ black hole. The temperature of the gauge theory is given by the Hawking temperature of the black hole, and the entropy is given by the Hawking-Beckenstein formula. The result is that the entropy density of the strongly coupled field theory is equal to $3/4$ of the free field theory value.\footnote{This implies that thermodynamics is not drastically effected in going from weak to strong coupling.}}

The crossover from weak to strong coupling can also be studied in the context of cold atomic gases. In the non-interacting limit the energy per particle is given by $E/N = 3E_F/5$. The Fermi energy $E_F = k_F^2/(2m)$ is related to the density $N/V = k_F^3/(3\pi^2)$. In the BCS limit interactions reduce the energy per particle. To leading order in $(k_Fa)$ we have

$$
\frac{E}{N} = \frac{3E_F}{5} \left\{ 1 + \frac{10}{9\pi} (k_Fa) + \ldots \right\}.
$$

In the unitarity limit $(k_Fa) \to \infty$ the energy per particle must be a universal constant times the free Fermi gas result, $E/N = \xi(3E_F/5)$. The calculation of the dimensionless quantity $\xi$ is a non-perturbative problem. The most accurate results for $\xi$ are believed to come from Green Function Monte Carlo (GFMC) calculations. Carlson et al. find\footnote{Carlson et al. find $\xi = 0.44$. This value is consistent with recent experimental determinations. GFMC calculations also show that the crossover from weak to strong coupling is smooth.} $\xi = 0.44$. It is interesting to find analytical approaches to the equation of state in the
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unitarity limit. We have recently summarized this subject in Ref. 6). There are a number of methods that can be systematically improved:

- An expansion in the number of species. At leading order this is essentially the BCS approximation, and higher orders take into account fluctuations around the BCS mean field. The result is \( \xi = 0.59 + O(1/N) \).

- An epsilon expansion around \( d = 4 \) or \( d = 2 \). The \( 4 - \epsilon \) expansion involves weakly coupled bosons and fermions, while the \( 2 + \epsilon \) expansion is related to the perturbative \((k_F a)\) expansion. The most reliable results are obtained by combining the two methods. Arnold et al. conclude that \( \xi = (0.30 - 0.37) \).

- An expansion in one over the number of spatial dimensions. This method corresponds to the hole line expansion of Bethe and Brueckner. The pair condensation energy is formally suppressed by \( 1/d \). The leading order result is \( \xi = 1/2 + O(1/d) \).

The various methods emphasize different aspects of the physics of a cold fermion gas, and they all have their advantages and disadvantages. None of them appear to converge rapidly.

§3. Transport properties

The matter produced at RHIC is characterized by strong radial and elliptic flow. This observation has lead to the conclusion that the shear viscosity to entropy density ratio of the quark gluon plasma at temperatures near \( T_c \) must be very small, \( \eta/s \ll 1 \). In the weak coupling limit the shear viscosity can be computed in perturbative QCD. The result is

\[
\eta/s = \frac{5.12}{g^4 \log(2.42g^{-1})}. \tag{3.1}
\]

In a weakly coupled \((g \sim 1)\) QGP \( \eta/s \) is very large. The shear viscosity to entropy density ratio decreases as the coupling increases, but it is hard to extrapolate the weak coupling result to the strong coupling domain. Kovtun et al. conjectured that there is a universal lower bound \( \eta/s \geq \hbar/(4\pi k_B) \). The bound is saturated in the case of strongly coupled gauge theories that have a gravity dual, like the \( \mathcal{N} = 4 \) SUSY gauge theory discussed in §2.

In cold atomic gases we can reliably compute \( \eta/s \) in the BCS limit. The ratio is temperature dependent and has a minimum at \( T \sim T_F \), where \( T_F = E_F/k_B \) is the Fermi temperature. The shear viscosity is proportional to \( 1/a^2 \), and \( \eta/s \) is very large in the weak coupling limit. As in the QCD case, there are no controlled strong coupling calculations. It is possible, however, to reliably extract \( \eta/s \) from experimental data on the damping of collective oscillations. Collective modes have been studied in a number of experiments. In the unitarity limit the frequency of collective modes is well described by ideal hydrodynamics. The energy dissipated due to viscous effects is

\[
\dot{E} = -\frac{1}{2} \int d^3 x \eta \left( \partial_i v_j + \partial_j v_i - \frac{2}{3} \delta_{ij} \partial_k v_k \right)^2 - \int d^3 x \, \zeta (\partial_i v_i)^2, \tag{3.2}
\]
Fig. 1. Viscosity to entropy density ratio of a cold atomic gas in the unitarity limit. This plot is based on the damping data published in Ref. 20) and the thermodynamic data in Refs. 21) and 22). The dashed line shows the conjectured viscosity bound $\frac{\eta}{s} = 1/(4\pi)$.

where $v_i$ is the flow velocity, $\eta$ is the shear viscosity and $\zeta$ is the bulk viscosity. In the unitarity limit the system is scale invariant and the bulk viscosity in the normal phase vanishes.

We recently analyzed the experimental data of the Duke group. Kinast et al. measure the damping rate of the radial breathing mode in an elongated, axially symmetric trap. They report measurements of the damping rate $\Gamma$ in units of the radial trap frequency as a function of $T/T_F$. The shear viscosity to entropy density ratio is given by

$$\frac{\eta}{s} = \frac{3}{4} \zeta^{1/2} (3N)^{1/3} \left( \frac{\Gamma}{\bar{\omega}} \right) \left( \frac{\bar{\omega}}{\omega_\perp} \right) \left( \frac{N}{S/N} \right),$$

where $\bar{\omega} = (\omega_\perp^2 + \omega_\parallel^2)^{1/3}$ is the geometric mean of the trap frequencies, $N$ is the number of atoms, and $S/N$ is the entropy per particle. Our results are shown in Fig. 1. We observe that $\eta/s$ has a shallow minimum near $T_c \sim T_F/3$. The value at the minimum is $\eta/s \sim 1/3$, roughly four times bigger than the proposed bound.

§4. Critical temperature

In the limit of high baryon density and low temperature the QCD phase diagram contains a number of color superconducting phases. Color superconductivity is characterized by the formation of quark Cooper pairs. At asymptotically large density the attraction is due to one-gluon exchange. In this limit the pairing gap is given by

$$\Delta = 2 \Lambda_{BCS} \exp\left(-\frac{\pi^2 + 4}{8}\right) \exp\left(-\frac{3\pi^2}{\sqrt{2}g}\right),$$

where $g$ is the running coupling constant evaluated at the scale $\mu$ and $\Lambda_{BCS} = 256\pi^4 (2/N_f)^5/2 g^{-5} \mu$. Here, $\mu$ is the baryon chemical potential and $N_F$ is the number of flavors. This result exhibits a non-BCS like dependence on the coupling constant which is related to the presence of unscreened magnetic gluon exchanges. The critical
temperature is nevertheless given by the BCS result $T_c = e^\gamma \Delta / \pi$.

In the weak coupling limit the gap and the critical temperature are exponentially small. The ratio $T_c / E_F$ increases with $g$ and reaches a maximum of $T_c = 0.025 E_F$ at $g = 4.2$. The maximum occurs at strong coupling and the result is not reliable. Using phenomenological interactions, or extrapolating the QCD Dyson-Schwinger equations into the strong coupling domain, one finds critical temperatures as large as $T_c = 0.15 E_F$.

At low temperature the atomic gas becomes superfluid. If the coupling is weak then the gap and the critical temperature can be calculated using BCS theory. The result is

$$\Delta = \frac{8 E_F}{(4e)^{1/3} e^2} \exp \left( -\frac{\pi}{2k_F|a|} \right) ,$$

(4.2)

where the factor $(4e)^{1/3}$ is the screening correction first computed by Gorkov et al. Higher order corrections are suppressed by powers of $(k_F a)$. In BCS theory the critical temperature is given by $T_c = e^\gamma \Delta / \pi$. Clearly, the critical temperature grows with the scattering length. Naively extrapolating Eq. (4.2) to the unitarity limit gives $T_c \simeq 0.28 E_F$. The value of $T_c$ has been determined in a number of Monte Carlo calculations. Burovski et al. find $T_c = 0.152(7) E_F$, while Bulgac et al. obtain $T_c = 0.23(2) E_F$ and Akkinei et al. quote $T_c = 0.25 E_F$. The larger values of $T_c$ are in better agreement with the transition observed in trapped systems.

§5. Stressed pairing

The exact nature of the color superconducting phase in QCD depends on the baryon chemical potential, the number of quark flavors and on their masses. If the baryon chemical is much larger than the quark masses then the ground state of QCD with three flavors is the color-flavor-locked (CFL) phase. The CFL phase is characterized by the pair condensate

$$\langle \psi_i^a C \gamma_5 \psi_j^b \rangle = \left( \delta_i^a \delta_j^b - \delta_j^a \delta_i^b \right) \phi .$$

(5.1)

This condensate leads to a gap in the excitation spectrum of all fermions and completely screens the gluonic interaction. Both the chiral $SU(3)_L \times SU(3)_R$ and color $SU(3)$ symmetry are broken, but a vector-like $SU(3)$ flavor symmetry remains unbroken. In the real world the strange quark mass is not equal to the masses of the up and down quark and flavor symmetry is broken. At high baryon density the effect of the strange quark mass is governed by the shift $\mu_s = m_s^2 / (2\mu)$ of the strange quark Fermi energy.

The response of the CFL state to a non-zero $\mu_s$ is a difficult problem that has not been fully resolved, even in the weak coupling limit. There are three energy scales that are important

- $m_K \sim (m_u m_s)^{1/2} (\Delta / \mu) \ll \Delta$ is the mass of the neutral strange Goldstone boson, the $K^0$. When $\mu_s > m_K$ the CFL phase undergoes a transition to a phase with kaon condensation.
Fig. 2. Conjectured phase diagram for a polarized cold atomic Fermi gas as a function of the scattering length $a$ and the difference in the chemical potentials $\delta \mu = \mu_\uparrow - \mu_\downarrow$, from Son and Stephanov (2005).

- $\mu_s^{(1)} \sim \Delta$ is the critical value of $\mu_s$ at which the first fermion mode becomes gapless. For $\mu_s > \mu_s^{(1)}$ the CFL phase (with or without kaon condensation) is a gapless superfluid.\(^{33}\)

- $\mu_s^{(2)} \sim 2\Delta$ is the critical value of $\mu_s$ beyond which CFL pairing breaks down completely. For $\mu_s > \mu_s^{(2)}$ the CFL phase is replaced by a less symmetric phase, like the 2SC phase or single flavor pairing in the spin-one channel.

The most difficult part of the phase diagram is the region $\mu_s^{(1)} < \mu_s < \mu_s^{(2)}$. Gapless fermion modes cause instabilities in the superfluid density and the magnetic screening masses.\(^{34}\) Near $\mu_s^{(1)}$ this instability can be resolved by a small Goldstone boson current.\(^{35}\) Closer to $\mu_s^{(2)}$ the Goldstone boson current may become large, and multiple currents can appear. In this limit the ground state is more appropriately described as a LOFF phase.\(^{36}\) We shall describe the LOFF state in more detail below.

The atomic superfluid involves equal numbers of spin up and spin down fermions. The physical situation which is analogous to the response of the CFL phase to $m_s$ is the response of the atomic superfluid to a non-zero chemical potential coupled to the third component of spin, $\delta \mu = \mu_\uparrow - \mu_\downarrow$. A conjectured (and, most likely, oversimplified) phase diagram for a polarized gas is shown in Fig. 2. In the BEC limit the gas consists of tightly bound spin singlet molecules. Adding an extra up or down spin requires energy $\Delta$. For $|\delta \mu| > \Delta$ the system is a homogeneous mixture of a Bose condensate and a fully polarized Fermi gas. This mixture is stable with respect to phase separation.

In the BCS limit the problem was first analyzed by Larkin, Ovchinnikov, Fulde and Ferell (LOFF).\(^{37}\) Consider the homogeneous solutions to the BCS gap equation for $\delta \mu \neq 0$. In the regime $\delta \mu < \Delta_0$ where $\Delta_0 = \Delta(\delta \mu = 0)$ the gap equation has a solution with gap parameter $\Delta = \Delta_0$. This solution is stable if $\delta \mu < \Delta_0/\sqrt{2}$ but only meta-stable in the regime $\Delta_0/\sqrt{2} < \delta \mu < \Delta_0$. The BCS solution has vanishing
polarization. The transition to a polarized normal phase is first order, and systems at intermediate polarization correspond to mixed phases.

LOFF studied whether it is possible to find a stable solution in which the gap has a spatially varying phase

$$\Delta(x) = \Delta e^{2i\vec{q} \cdot \vec{x}}.$$ (5.2)

This solution exists in the LOFF window \(\delta \mu_1 < \delta \mu < \delta \mu_2\) with \(\delta \mu_1 = \Delta_0 / \sqrt{2} \approx 0.71 \Delta_0\) and \(\delta \mu_2 \approx 0.754 \Delta_0\). The LOFF momentum \(q\) depends on \(\delta \mu\). Near \(\delta \mu_2\) we have \(qv_F \approx 1.2 \delta \mu\), where \(v_F\) is the Fermi velocity. The gap \(\Delta\) goes to zero near \(\delta \mu_2\) and reaches \(\Delta \approx 0.25 \Delta_0\) at \(\delta \mu_1\).

These results suggest that for some value of the scattering length between the BEC and BCS limits the homogeneous superfluid becomes unstable with respect to the formation of a non-zero supercurrent \(\vec{V} \varphi\), where \(\varphi\) is the phase of the condensate. We can study the onset of the instability using the effective Lagrangian

$$\mathcal{L} = \psi^\dagger \left( i\partial_0 - \epsilon(-i\vec{\partial}) - i(\vec{\partial} \varphi) \cdot \frac{\vec{\partial}}{2m} \right) \psi + \frac{f_1^2}{2} \varphi^2 - \frac{f_2^2}{2} (\vec{\partial} \varphi)^2.$$ (5.3)

Here, \(\psi\) describes a fermion with dispersion law \(\epsilon(\vec{p})\) and \(\varphi\) is the superfluid Goldstone mode. The low energy parameters \(f_1\) and \(f_2\) are related to the density and the velocity of sound. Setting up a current \(\vec{v_s} = \vec{\partial} \varphi / m\) requires energy \(f_1^2 m^2 v_s^2 / 2\). The fermion dispersion law in the presence of a non-zero current is \(\epsilon_v(\vec{p}) = \epsilon(\vec{p}) + \vec{v_s} \cdot \vec{p} - \delta \mu\), and a current can lower the energy of the fermions. The free energy functional was analyzed by Son and Stephanov.\cite{38} They noticed that the stability of the homogeneous phase depends crucially on the nature of the dispersion law \(\epsilon(p)\). In the BEC limit the minimum of the dispersion curve is at \(p = 0\) and there is no current instability. In the BCS limit the minimum is at \(p \neq 0\), the fermion contribution is amplified by a finite density of states on the Fermi surface, and the system is unstable with respect to the formation of a non-zero current.

There is an ongoing effort dedicated to the experimental study of the phase diagram as a function of scattering length, polarization, and temperature. We cannot adequately summarize all of these experiments here. The MIT group has mapped out the superfluid-normal transition line in the \((\delta \mu, a)\) plane.\cite{39} In the unitarity limit the transition occurs at a population imbalance \((n_{\uparrow} - n_{\downarrow})/(n_{\uparrow} + n_{\downarrow}) \approx 70\%\). Currently, there is no evidence for inhomogeneous or anisotropic states like the LOFF phase.

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