Annals of Physics 370 (2016) 105–116

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Low temperatures shear viscosity of a two-component dipolar Fermi gas with unequal population

E. Darsheshdar, H. Yavari *, Z. Zangeneh

Department of Physics, University of Isfahan, Isfahan 81746, Iran

ARTICLE INFO

Article history:
Received 16 May 2015
Accepted 21 March 2016
Available online 12 April 2016

Keywords:
Dipolar Fermi gas
Green's functions
Spin polarized
Shear viscosity

ABSTRACT

By using the Green's functions method and linear response theory we calculate the shear viscosity of a two-component dipolar Fermi gas with population imbalance (spin polarized) in the low temperatures limit. In the strong-coupling Bose–Einstein condensation (BEC) region where a Feshbach resonance gives rise to tightly bound dimer molecules, a spin-polarized Fermi superfluid reduces to a simple Bose–Fermi mixture of Bose-condensed dimers and the leftover unpaired fermions (atoms). The interactions between dimer–atom, dimer–dimer, and atom–atom take into account to the viscous relaxation time (τ_η). By evaluating the self-energies in the ladder approximation we determine the relaxation times due to dimer–atom (τ_{DA}), dimer–dimer (τ_{cDD}, τ_{dDD}), and atom–atom (τ_{AA}) interactions. We will show that relaxation rates due to these interactions τ_{DA}^{-1}, τ_{cDD}^{-1}, τ_{dDD}^{-1}, and τ_{AA}^{-1} have T^2, T^4, e^{-E/k_BT} (E is the spectrum of the dimer atoms), and $T^{3/2}$ behavior respectively in the low temperature limit ($T \to 0$) and consequently, the atom–atom interaction plays the dominant role in the shear viscosity in this rang of temperatures. For small polarization ($\tau_{DA}, \tau_{AA} \gg \tau_{cDD}, \tau_{dDD}$), the low temperatures shear viscosity is determined by contact interaction between dimers and the shear viscosity varies as T^{-5} which has the same behavior as the viscosity of other superfluid systems such as superfluid neutron stars, and liquid helium.

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* Corresponding author. Tel.: +98 3119732432; fax: +98 3117932409.
E-mail addresses: h.yavary@sci.ui.ac.ir, hs_yavary@yahoo.com (H. Yavari).

http://dx.doi.org/10.1016/j.aop.2016.03.007
0003-4916/

1. Introduction

An impressive amount of experimental and theoretical work has characterized the investigation of ultracold dipolar quantum Bose and Fermi gases in the last few years [1–11]. Bose–Einstein condensations of dipolar chromium atoms, which possess a magnetic dipole moment six times larger than that of alkali atoms, have been realized experimentally [2].

Besides chromium, heteronuclear molecules and Rydberg atoms are also expected to interact via a strong dipole–dipole force due to their large electric dipole moment [5–8]. If atomic dipole moments are sufficiently large, the resulting dipole–dipole forces may influence, or even completely change the properties of cold Bose and Fermi gases. Cold dipolar atom gases have attracted a lot of attention due to the novel anisotropic and long-range character of dipole–dipole interactions.

Recent studies of many-body effects predicted an elongated Fermi surface in a one-component fully polarized Fermi gas with dipolar interactions, along the polarization direction created by an external field [3]. The properties of the superfluid dipolar Fermi gas are different from those of a two-component fermionic gas with s-wave pairing due to a short-range inter-component interaction. In the case of the s-wave pairing, order parameter is isotropic, while it is anisotropic in the superfluid dipolar Fermi gas. Interparticle interactions in realistic polarized dipolar gases include both a short-range Van der Waals part and a long range dipole–dipole one. At large interparticle separations only the dipole–dipole part survives. In a single component Fermi gas, due to the Pauli principle, the contribution of the short-range part of the interparticle interaction can be neglected, and therefore, the dominant interaction between particles is the dipole–dipole one. The dipole–dipole interaction is anisotropic and, as a result, it mixes scattering channels with different angular momenta. Additionally, the dipole–dipole interaction is partially repulsive (when two particles are side by side to each other) and partially attractive (when they are on top of each other). This means that, similarly as for dipolar Bose gases, the properties of the system depend on the trap geometry [12]. Owing to the long-range and anisotropic nature of the dipole–dipole interaction new quantum phenomena emerge in the dipolar Fermi gases. Of particular interest, the recent studies demonstrated that in the two-species dipolar Fermi gases the competition between the short-range contact interaction and dipole–dipole interaction led to the coexistence of singlet- and triplet-paired superfluids [13–15].

The Fermi liquid properties of the cold atomic dipolar Fermi gases with the explicit dipolar anisotropy by using perturbative approaches have been studied [16]. The ground state and BCS superfluidity of a dipolar Fermi gas have also been investigated theoretically [17,18].

The transport properties of superfluid phase in the previous studies have relied heavily on the Boltzmann equation approach [4,19–21]. The linear response theory and Kubo formulae approach has been less widely applied. The advantage of Kubo formula approach, however, is that by relating directly to diagrammatic Green's function one has better control over the processes included in transport and the appropriate constraints. Kubo formula approach takes into account the presence of the pseudogap in the spectral density of states for single-particle excitations [22]. Obtained results from Kubo formula are close to the Boltzmann equation one at high temperatures and weak interactions.

The use of a Boltzmann equation implicitly assumes the existence of quasiparticles with a well definite energy–momentum relationship. When the spectral functions broaden, the quasiparticles are less well defined, and it therefore becomes relevant to investigate the effect of this broadening on the transport properties of the gas. Ideally, one should derive a kinetic equation that takes all strong-coupling effects systematically into account, but due to the lack of a small parameter in the strong-coupling limit this would be far too ambitious an undertaking.

In the BEC region of the spin polarized Fermi superfluid, all of the minority species of fermions are paired up (dimers), leaving a gas of the remaining fermions (atoms). Thus in this region, a spin-polarized Fermi gas should behave like a Bose–Fermi mixture of the dimer molecules and unpaired atoms. The different quantum-statistical behavior of these two components (boson and fermion) gives rise to fundamentally novel quantum many-body phases. To described the transport coefficients, such as viscosity of these systems the Kubo-based formalism is used which readily accommodates the simultaneous bosonic and fermionic contributions while the alternative Boltzmann or kinetic theory-based approaches do not naturally incorporate the multiple statistical effects. The Kubo approach includes scattering processes via the lifetimes [23] which appear in the