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Thermal conductivity of spin-polarized liquid ^3He

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Abstract

We present the first measurements of the thermal conductivity of spin-polarized normal liquid ^3He . Using the rapid melting technique to produce nuclear polarizations up to 0.7, and a vibrating wire both as a heater and a thermometer, we show that, unlike the viscosity, the conductivity increases much less than predicted for s-wave scattering. We suggest that this might be due to a small probability for head-on collisions between quasiparticles.

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Strongly correlated fermionic systems are common in nature, in fields as diverse as condensed matter physics (including heavy fermion systems and high critical temperature superconductors), nuclear physics (nuclear matter), and astrophysics (neutron stars). Since the 1950's, liquid ^3He has been heavily studied as a model for such systems. Although simpler than the electronic 'gas' in metals (^3He atoms are neutral and spin 1/2, and there is no underlying lattice), liquid ^3He is also characterized by strong interactions between particles. Unlike in the recently obtained ultracold Fermi gases, the interaction results from the large density rather than from a resonant scattering process, and is not restricted to a given scattering channel. Both $k_F a$ and $k_F R$ are of order unity in liquid ^3He , where k_F is the Fermi wavevector, R the range of interaction, and a the scattering length, while only the former holds in ultracold Fermi gases [1]. One then expects transport in degenerate ^3He to involve not only s-wave scattering, but also partial waves with orbital angular momentum $l > 0$ [2]. Accordingly, in unpolarized liquid ^3He , the experimental values of the longitudinal transport coefficients (thermal conductivity, viscosity, and spin diffusivity) are better accounted for by the s-p approximation, where both $l = 0$ and $l = 1$ are taken into account, than by a simple s-wave calculation [3]. More sophisticated models, such as the induced interaction model [4], give even better agreement. A more direct test of the nature of the scattering, however, is to measure the dependence of the transport coefficients on the spin polarization.

Transport coefficients in a system of interacting fermions are indeed sensitive to the spin polarization m . When the de Broglie wavelength is larger than R , the Pauli principle requires that collisions between particles take place in a globally antisymmetric state, coupling the spin and orbital degrees of freedom. This effect has been theoretically studied, both in non-degenerate [5, 6] and degenerate [7–10] systems. In dilute systems, i.e., when the distance between particles is $\gg R$, and at low temperature, collisions only take place in the $l = 0$ state (pure s-wave scattering,) and are thus suppressed by polarization, which increases the transport coefficients. This has been demonstrated in degenerate dilute ^3He - ^4He mixtures ; for a ^3He polarization of 99%, the viscosity is $100\times$ that of the unpolarized mixture [11, 12]. This suppression explains why Fermi gases of atoms in a given spin state can only be evaporatively cooled by mixing them with different spin states [13] or atoms [14]. Beyond the s-wave limit, collisions with non-zero l come into play. Their effect has been calculated for non-degenerate dilute gases only [15], and account for the polarization dependence of thermal conductivity in gaseous ^3He around 2 K [16]. In liquid ^3He , no such detailed prediction exists,

but, due to the significant weight of the p-wave ($l = 1$) channel, scattering is not expected to be suppressed as strongly on polarization as in dilute systems. The only transport property measured so far as a function of polarization has been the viscosity [17, 18]. The most recent measurements [19] show that it increases linearly with m^2 with a slope in agreement with the s-wave prediction [7, 9], despite the strong p-wave scattering component. This puzzle calls for the measurement of the thermal conductivity of spin-polarized liquid ^3He .

To this end, we use the rapid melting technique [20] to produce highly, but transiently, polarized liquid ^3He , and probe its thermal conductivity κ with a vibrating wire viscometer, previously used to determine the viscosity [19]. Injecting heat into this wire raises the temperature of the surrounding liquid, which we detect through the induced change in viscosity η ($\propto 1/T^2$ at low temperature). This allows us to measure the thermal conductivity on a short time scale (\sim s). The ^3He sample is confined in a silver sinter with a 200 μm wide slit in its center containing the vibrating wire viscometer, which has resonance frequency 10 kHz and quality factor 4000 in vacuum. The viscometer is a 30 μm diameter manganin wire (total length 90 mm and resistance 45 Ω) bent into a 2 mm diameter loop. We excite the viscometer with a several μA_{RMS} AC current at fixed frequency near the resonance and measure the in- and out-of-phase components of the induced voltage, enabling determination of the width of the resonance, which gives the viscosity of the liquid through Stokes's formula. We then superimpose a DC current with an applied power per unit length of wire \dot{Q} to the AC driving current, which results in Joule heating of the resistive wire, and measure the induced change in viscosity. Because the viscous penetration depth in our experiments is 2–4 μm , much smaller than the slit width, the temperature measured is that around the wire. Since the temperature of the walls of the cell is regulated, its increase δT equals $R_{th}\dot{Q}$, where R_{th} is the thermal resistance between the wire and the cell walls. Due to the quasi-1D heating geometry, R_{th} is dominated by the contribution $\propto 1/\kappa$ of the ^3He around the wire. Systematic measurements in unpolarized liquid [21, 22] allowed us to check the reliability of this method, in particular that the heat goes entirely into the liquid, rather than being partly evacuated through the wire [22].

Starting with 0.1 cm^3 solid ^3He polarized to 80% at 5 mK, 11 T, and \simeq 34 bar, we rapidly melt the solid by depressurizing it to 27 bar. At this pressure, the polarization [23] of the resulting liquid, measured with a high field squid magnetometer [24], decays from its initial value (70%) to its small equilibrium value $m_0 \simeq$ 4% on a 60 s timescale. Melting releases a

large amount of heat, which is absorbed by a thermal reservoir of unpolarized liquid ^3He , to which the sample cell is thermally anchored. The resulting temperature, right after melting, is about 50 mK. The temperature of the thermal reservoir is then regulated at a somewhat larger value; the heat released by depolarization keeps the sample ^3He temperature T above that of the reservoir. T , which coincides with the temperature of the viscometer in its cold state, is measured by a carbon thermometer, located in the slit 2 mm from the viscometer. The thermal conductivity is measured during depolarization by switching on and off the DC current every 6–9 s. Typical values for the currents and powers resulting in a 5 mK temperature change at 60 mK are 250 μA and 70 nW/mm.

Figure 1 shows the viscosity with modulated DC current versus m^2 for two experiments at 27 bar and regulated reservoir temperatures of 66 mK and 76 mK. The viscosity in the cold state (no DC current) varies with m , due to, first, its intrinsic polarization dependence, and, second, the decrease of the ^3He temperature to the base temperature as m relaxes to equilibrium. To determine the temperature of the hot state, when the viscometer is out of equilibrium with the carbon resistor, from the measured viscosity $\eta(m, T + \delta T)$, we note that, at low temperature enough, the ratio $f(m) \equiv \eta(m, T)/\eta_0(T)$ is independent of T , because both $\eta_0 \equiv \eta(m_0, T)$ and $\eta(m)$ vary as $1/T^2$. The ratio of hot to cold viscosities in the polarized state (measured as described in the inset of figure 1) is therefore equal to that in the unpolarized state for the same temperatures:

$$\frac{\eta(m, T + \delta T)}{\eta(m, T)} = \frac{\eta_0(T + \delta T)}{\eta_0(T)}. \quad (1)$$

From this ratio, the temperature T read by the carbon thermometer, and $\eta_0(T)$ measured immediately after the rapid melting experiment, we determine δT and therefore $R_{th}(m, T)$. To correct for the change in R_{th} with T (T decreases by about 15 mK during depolarization, resulting in a 3% change in R_{th}), we divide $R_{th}(m, T)$ by the thermal resistance in the unpolarized state $R_{th}(m = m_0, T)$, measured like $\eta_0(T)$ after the melting experiment. The last step is to convert R_{th} to the ^3He thermal conductivity. Modelling of the thermal characteristics shows that R_{th} , although dominated by the ^3He around the wire, has smaller contributions from the finite thermal conductivity of the silver sinter and the Kapitza resistance between ^3He and the sinter. We experimentally determined the sensitivity of R_{th} to κ by varying the latter by changing the pressure in unpolarized ^3He [21]. For the range of R_{th} values observed in polarized ^3He , we find $R_{th} \propto \kappa^{-0.7}$. This is consistent with the mod-

elling based on the thermal parameters measured in Ref. [25], which predicts an exponent of -0.78 .

Based on the experimental exponent -0.7 , figure 2 shows the polarization dependence of κ for a series of experiments at a base temperature of 66 mK, using different levels of AC drive and DC heating, corresponding to changes in temperature of 5 to 20%. Two experiments at 55 and 76 mK are also shown. In contrast to the viscosity, which changes by more than a factor of 2 up to $m = 0.6$, κ only weakly increases with polarization, by less than 20% in the same polarization range. This is a much smaller effect than the prediction of the s-wave theory, also shown in figure 2. This difference with a s-wave behavior is beyond our experimental uncertainties. In particular, as we discuss in the following paragraph, the assumption that $f(m, T)$ is temperature independent might affect the results only above $m = 0.4$. At this polarization, the measured conductivity is, at most $1.04\times$ its unpolarized value, while the predicted value is 30% larger.

This difference cannot be due to systematic errors either. The precision on the measured thermal resistance R_{th} depends on the noise on η compared to its modulation, on the precision of the fitting procedure (especially for large polarizations, i.e., small times, when the rate of change in η is large), and on how accurately the carbon thermometer measures the temperature in the cold state. Altogether, we estimate a systematic error on κ of 2–3% for $m < 0.4$ and at most 7% above, consistent with the repeatability of the experiments. The influence of the assumption of a temperature independent $f(m, T)$ can also be evaluated. If $f(m, T)$ depends on T , the right hand side of Eq. 1 has to be multiplied by $f(m, T + \delta T)/f(m, T)$, which modifies the inferred δT . In principle, the temperature dependence of $f(m, T)$ can be determined from the two experiments at different base temperatures shown in figure 1. For $m \approx 65\%$, $f(m, T)$ changes by 3% for a temperature change of 10%, to be compared to a 15% change of η_0 . Assuming that such a small change is not an artefact [26], we can take it into account in the following way. At a given polarization, we get from the two curves of figure 1 the cold state viscosity at two temperatures of the inner thermometer. We then deduce, for the experiment at the base temperature of 66 mK, the hot state ^3He temperature, hence δT , by interpolation. The result in terms of κ is shown as a continuous line in figure 2. Because f tends to unity at small polarizations, this line differs from the above analysis for $m > 0.4$ only. As stated above, the result is that, whatever choice we make, and in contrast with that of the viscosity, the polarization dependence of

the thermal conductivity is smaller than predicted by the s-wave theory.

Our analysis ignores the effects of the Onsager coupling of heat and spin currents [8–10], which could influence the results in two ways. First, the applied temperature difference leads to a polarisation current away from the viscometer. Because the spin diffusion time inside the slit is smaller than the temperature modulation timescale, the spins inside the slit redistribute during heating so to reach a steady-state distribution. The induced polarization gradient, such that the diffusive current cancels the thermally induced current, depends on the ratio of the spin thermal diffusion to the usual spin diffusion. This gradient contributes to the energy flux, with a sign opposite to the contribution of the temperature gradient. As a result, the conductivity measured ignoring this effect is too small. This effect is likely to be small: For s-wave scattering, the correction computed from [10] is less than 2%. Second, the induced polarization gradient decreases the viscosity around the wire, hence increases the inferred temperature. Using [8] to compute the polarization change for s-wave scattering [27], and the measured dependence of viscosity on polarization, we find that this effect decreases the measured conductivity by 7% at $m = 0.4$, an amount too small to account for the observed difference between our measurements and the s-wave prediction. We have not corrected the data for these effects, because the Onsager coefficients for ^3He are not known. If the Onsager coefficients were much greater in ^3He than expected from comparison with the dilute gas, the measured data could represent a combination of thermal resistance and Onsager effects, but this would prove as well that liquid ^3He does not behave like a dilute gas.

The difference between our results and the s-wave prediction leads us to consider the effect of p-wave scattering. Exact calculation gives the transport coefficients of polarized liquid ^3He in terms of the (polarization-dependent) Fermi momenta of the spin up and down quasiparticles, and their scattering amplitudes [28, 29]. These amplitudes are only known at zero polarization and in the forward direction, where they are related to the Landau coefficients. Assuming that these amplitudes do not depend on polarization, and that their angular dependence is fixed by the s-p approximation [3], we can compute the effect of polarization by solving the exact equations derived in Ref. [29]. As shown in figure 2, the dependence is closer to our observations than the s-wave prediction, but remains too strong. However, these calculations also show that the polarization dependence is very sensitive to the angular dependence assumed for the zero polarization scattering amplitude. This can

be understood from the following argument [30]. When the Fermi spheres for up and down spins differ in diameter, the head-on collisions where a majority (say up) spin would invert its momentum become forbidden. For a dilute gas with isotropic scattering, this makes unavailable a fraction of the up spin Fermi surface, of order m . As discussed by Nozières [31], this suppression implies an initial linear increase of the thermal conductivity with m , which is indeed predicted over a wide range of polarizations [32]. Hence, the more head-on collisions are unfavoured in liquid ^3He , the smaller will be the polarization dependence. The difference between our results and the s-p approximation would thus point to a reduced scattering amplitude for head-on collisions, compared to this approximation. It is interesting to note that, at saturated vapor pressure, such a reduction is predicted by the Ainsworth-Bedell [4] induced interaction model.

In conclusion, the polarization dependence of the thermal conductivity of spin polarized liquid ^3He is smaller than predicted by s-wave scattering, being less than 20% up to a polarization of 0.6, if the Onsager cross term has a negligible effect. This weak dependence is qualitatively consistent with the idea that scattering in ^3He is forward-biased, important information for, e.g., the calculation of the critical temperature for superfluidity [33, 34]. Although this difference with a dilute gas is not unexpected for a dense liquid, it contrasts with the behavior of viscosity. It remains a challenge for theory to explain both behaviors at the same time.

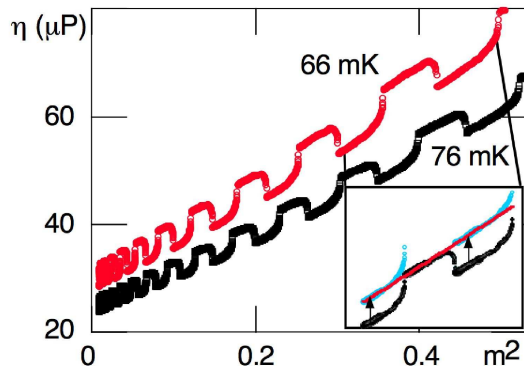
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Sawkey et al : fig 1

FIG. 1: Polarization dependence of the viscosity for two experiments regulated at 66 and 76 mK ; the heating DC current is switched between 0 and $250 \mu\text{A}$ every 9 s and 7 s, respectively. Time increases from right to left. The inset shows how we determine the ratio of the viscosity in the cold (i.e. large viscosity) and hot states. For each sequence of three states (dark line), we eliminate the transients by keeping the 4 last seconds of each step (thick line). $\eta(m, T + \delta T)/\eta(m, T)$ is determined such that, after correction of the first and last steps (blue line) by this ratio, the data lie on a single local parabola (thin red line). Associating the obtained δT with the polarization of the intermediate step gives $R_{th}(m)$.

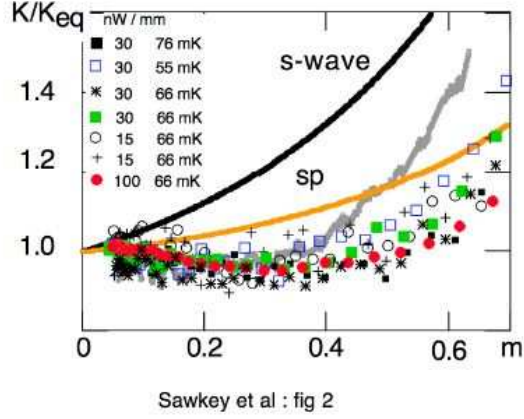
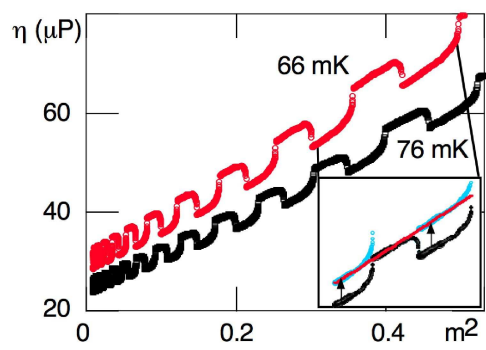


FIG. 2: (Color online) Polarization dependence of the thermal conductivity of ${}^3\text{He}$ $\kappa(m)/\kappa(m_0)$, for a series of experiments at 27 bar, for different base temperatures and heating powers. The points are obtained assuming a temperature independent f (see text). The dark and open squares correspond to the experiments of fig. 1. The continuous thick line corresponds to the interpolation scheme described in the text, when the above assumption is not made. The experimental polarization dependence is smaller than predicted for s-wave scattering or the s-p approximation, respectively shown by the black and grey (orange online) continuous lines.



Sawkey et al : fig 1

Figure 1

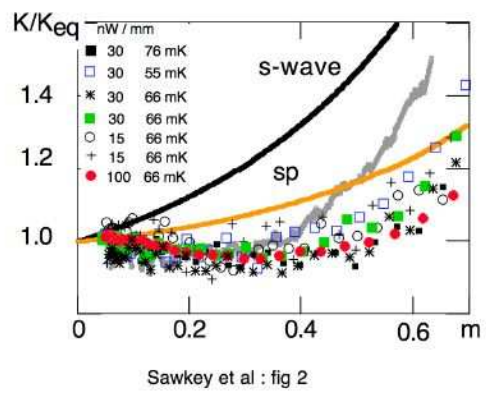


Figure 2