New Evidence for Zero-Temperature Relaxation in a Spin-Polarized Fermi Liquid

H. Akimoto,1, 2 D. Candela,1 J. S. Xia, 2 W. J. Mullin,1 E. D. Adams, 2 and N. S. Sullivan2

1 Physics Department, University of Massachusetts, Amherst, MA 01003
2 Microkelvin Laboratory, NHMFL, and Physics Department, University of Florida, Gainesville, FL 32611
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Spin-echo experiments are reported for 3He–4He solutions under extremely high B/T conditions, B = 14.75 T and T ≥ 1.73 mK. The 3He concentration \( x_3 \) was adjusted close to the value \( x_c \approx 3.8\% \) at which the spin rotation parameter \( \mu M_0 \) vanishes. In this way the transverse and longitudinal spin diffusion coefficients \( D_\perp, D_\parallel \) were measured while keeping \( |\mu M_0| < 1 \). It is found that the temperature dependence of \( D_\perp \) deviates strongly from \( 1/T^2 \), with anisotropy temperature \( T_a = 4.26 \pm 0.18 \) mK. This value is close to the theoretical prediction for dilute solutions, and suggests that spin current relaxation remains finite as the temperature tends to zero.

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A fundamental result of Fermi liquid theory is that the quasiparticle scattering time and hence the transport coefficients diverge as the temperature tends to zero. Recently, there has been much interest in the possibility that spin polarization could remove this divergence for transverse spin currents by creating scattering phase space between spin-up and spin-down Fermi surfaces. A kinetic equation for dilute systems has been questioned by Fomin, and a recent experiment based on spin waves rather than spin echoes found that the effect is much weaker than previously measured, if indeed it exists at all. The origin of the theoretical disagreement is unclear. In Ref. 3 a kinetic equation for dilute systems was solved to deduce the existence of zero-temperature attenuation, while in Ref. 4 field-theory methods were used to reach a similar conclusion. Conversely, in Ref. 3 it was argued that a proper separation of hydrodynamic variables shows that long-wavelength transverse spin currents are not relaxed at zero temperature.

In this paper we present new experimental evidence that polarization-induced relaxation does indeed occur in 3He–4He, although observation of the effect requires higher fields and/or lower temperatures than previously thought necessary. Our results for a 3.8% 3He–4He solution are consistent with the theoretical prediction for extremely dilute solutions, unlike the earlier results. Although we use NMR spin echoes, in common with earlier experiments that showed polarization-induced relaxation, we have picked 3He concentrations \( x_3 \) very near the critical concentration \( x_c \approx 3.8\% \) at which the spin rotation parameter \( \mu M_0 = -\Omega T \) vanishes. This is significant because effects that destroy spin echo coherence such as restricted diffusion and spin-wave instabilities can limit the apparent magnitude of \( \mu M_0 \), mimicking a departure from \( D \propto 1/T^2 \). The earlier experiments were all in the regime \( |\mu M_0| >> 1 \) apart from one experiment that used a field/temperature ratio \( B/T \) ten times lower than that employed in the present work. By adjusting \( x_3 \) to within 0.02% of \( x_c \) we achieved the condition \( |\mu M_0| < 1 \) at our highest \( B/T = (14.75 \) T)/(1.73 mK). Thus, we have carried out an experiment showing significant spin-diffusion anisotropy \( D_\parallel/D_\perp > 5 \) which is robust against possible effects of large \( |\mu M_0| \).

The magnitude of polarization-induced relaxation is characterized by an “anisotropy temperature” \( T_a \), defined by fitting the transverse diffusion coefficient to

\[
D_\perp(T) \propto 1/(T^2 + T_a^2). \tag{1}
\]

This form implies that \( D_\perp \) tends to a constant value as the temperature is lowered well below \( T_a \), hence the term “zero temperature” relaxation. For extremely dilute 3He–4He solutions, it is predicted that \( T_a = \mu B/(2\pi k_B) = (248 \mu K)/B \) where \( \mu_3 \) is the 3He nuclear magnetic moment. Therefore, very high \( B/T \) ratios exceeding 4000 K/T are required to measure \( T_a \), unless nonequilibrium spin polarization is used as in Ref. 5.

To reach these conditions in equilibrium, we have employed a nuclear demagnetization cryostat that incorporates a 15 T NMR-grade sample magnet, which was oper-
The sample inside the NMR cavity is in excellent thermal contact with the sample in the main cell (measured time constant ≈ 150 ms at the base temperature), due to the $T^{-1}$ temperature dependence of the sample thermal conductivity. The mechanical analysis for this composite viscometer and its calibration as a high $B/T$ thermometer will be detailed elsewhere [18].

The $^3$He concentration $x_3$ was determined to within ±0.08% (i.e. relative uncertainty of 2%) by measuring the quantities of gas added to the sample cell. To precisely adjust $x_3$ to $x_c$, small quantities of $^4$He were added to the cell between temperature scans. Thus, the differences between $x_3$ values are known to within ±0.005%.

The transverse spin diffusion coefficient $D_\perp$ and spin-rotation parameter $\mu M_0$ were measured by observing the amplitude $h$ and phase $\phi$ of the spin echoes formed by the two-pulse sequence $\theta$--$t/2$--$180^\circ$--$t/2$--echo. Here $\theta = 8^\circ$ is the tipping angle of the first pulse and $t/2$ is the time between pulses. To measure $D_\perp$ and $\mu M_0$ at each temperature, a series of spin echo experiments with different delay times $t/2$ were carried out. The echo amplitude was fit to the following form, valid for $\theta \ll 90^\circ$ [10]:

$$he^{i\phi} = h_0 \exp[-\mathcal{D}(\gamma G)^2 t^3/12], \quad \mathcal{D} = \frac{D_\perp}{1 + i\mu M_0}.$$  (2)

The vertical static field gradient $G = 29.5 \pm 2.5$ G/cm applied to the sample was accurately measured by a least-squares fit to the shape of a single spin echo. The longitudinal spin diffusion coefficient $D_\parallel$ was measured by the recovery of the longitudinal magnetization following its modification by a pulse of tip-angle $\theta' = 30^\circ$ and subsequent decay of the transverse components (pulse sequence $30^\circ$--$t$--$8^\circ$) [24].

Figure 3 shows spin echo data for three closely spaced values of $x_3$, along with fits to Eq. [2]. Despite the wide variation of $\mu M_0$ and the echo decay time, the fitted $D_\perp$ values agree to within ±12%. This is further evidence that effects that might limit the apparent magnitude of $\mu M_0$ have not significantly affected the measured value of $D_\perp$. Figures 2 and 3 show the data for $D_\perp$ and $D_\parallel$ respectively for several concentrations $x_3$ near the critical concentration $x_c$. Table 4 shows the results of fitting these data to

$$D_{\perp,\parallel}(T) = C_{\perp,\parallel}/(T^2 + T_{\perp,\parallel}^2).$$  (3)

Ideally we would find $C_{\perp} = C_\parallel$, $T_{\perp} = 0$ and $T_{\parallel}$ would be the experimental estimate of $T_c$. In fact, the difference between the fitted values for $C_{\perp}$ and $C_{\parallel}$ is within their combined uncertainties, and the fitted value for $T_{\parallel}$ is consistent with zero.

FIG. 1: Spin-echo amplitude as a function of time at temperatures near 2 mK for three slightly different values of the $^3$He concentration $x_3$. Circles, triangles, and squares show the magnitude, real, and imaginary parts respectively of the measured echo amplitude. The curves show fits to Eq. [3] which result in the values shown on each graph for the transverse spin diffusion coefficient $D_\perp$ and the spin rotation parameter $\mu M_0$. Even though $\mu M_0$ and thus the echo decay time varies rapidly with $x_3$, for all of these data $D_\perp$ is within 12% of the average value we measure at this temperature, $D_\perp = 4.46$ cm$^2$/s (Table 4). This should be compared with our measured value of the longitudinal diffusion coefficient at the same temperature, $D_\parallel = 16.6$ cm$^2$/s.
and we have calculated features in Ref. 21, we find that the initial and final temperature measurements is sample heating due to irreversible spin diffusion anisotropy temperature that would be due to this type of heating, in the absence of true spin diffusion anisotropy ($T_a = 0$). For the conditions of our experiment, we calculate $T_a = 1.23 \text{ mK}$ for $\theta = 8^\circ$ as used for the $D_\perp$ measurements, and $T_a = 3.3 \text{ mK}$ for $\theta = 30^\circ$ as used for the $D_\parallel$ measurements. Similar spin-diffusion heating occurs due to imperfections in the 180° pulse used to form spin echoes. However, we compute that the RMS deviation of the magnetization from a perfect 180° rotation is only 9° in our experiments, and any such heating would occur well after the main spin echo decay.

We have checked for several other possible conditions that might affect the $D_\parallel$ measurements: (1) The smaller of the spin mean free path and the spin rotation distance is never greater than 8% of the magnetization pitch for an echo decay of $1/e$, consistent with the requirements for the applicability of Leggett’s spin dynamic equation [19]. (2) Similarly, we find that for the conditions of our experiment, relaxing the “steady state” approximation $\partial J/\partial t = 0$ used in Ref. [19] never changes the apparent value of $D_\parallel$ by more than a few percent. (3) The fitted values of $\mu M_0$ are always much less than the apparent saturation value due to restricted diffusion found in Ref. [14], $\mu M_0/|\mu M_0|_{\text{sat}} \approx 0.3 b_L^{1/2}$. Here $b_L = L^3(\gamma G)\mu M_0/D_\perp$ where $L$ is the cell height.

In Figure 3, we show our data for the quantity $\mu M_0/D_\perp$. In Fermi-liquid theory, $\mu M_0/D_\perp$ is expected to be temperature independent, as both $\mu M_0$ and $D_\perp$ are proportional to the transverse spin current relaxation time $\tau_\perp$ [19]. The vanishing of $\mu M_0$ at $x_3 = x_c$ can be viewed as a result of cancellation between positive and negative portions of the quasiparticle interaction potential. Therefore, it is perhaps not surprising that this cancellation is upset by thermal excitation of the system, leading to a variation with temperature of $\mu M_0/D_\perp$. The observed variation is approximately linear in temperature (Fig. 4). We have checked that the temperature variation is the same on warming and cooling.

Our most important result is that $D_\perp$ follows Eq. 3 with a nonzero anisotropy temperature $T_a = 4.26 \pm 0.18 \text{ mK}$, as shown by the solid line fit in Fig. 4. We be-
FIG. 4: Measured ratio of spin rotation parameter $\mu M_0$ to transverse spin diffusion coefficient $D_\perp$ (data points), and linear fits (lines). In lowest-order Fermi liquid theory, this ratio should be independent of temperature, depending only upon the Fermi velocity and Fermi-liquid interaction parameters $F_0^\parallel$ and $F_0^\perp$. The dashed line shows the prediction of a calculation based on a phenomenological quasiparticle potential $V(q)$, evaluated for $x_3 = 3.65\%$.

believe this result is robust against the effect of spin heating ($T_a > T_b = 1.23$ mK, and the latter temperature would only be reached after the echoes fully decayed). It is possible that the spin dynamics are modified from Eq. $2$ at the special point $x_3 = x_c$ $[22]$, although we see no experimental evidence of this. Interestingly, our measured $T_a$ is nearly consistent with the theoretical value $\mu_3 B/2\pi k_B = 3.73$ mK predicted for very dilute solutions, and is considerably smaller than the value $22 \pm 3$ mK that is obtained by extrapolating earlier results for this $x_3$ to our higher field $[8]$. Recently Buu et al. reanalyzed NMR data taken at $x_3 = 6.1\%$ taking into account restricted diffusion effects, and concluded that $T_a$ is considerably smaller than previously thought, although still $2.2$ times larger than the dilute-solution value $[20]$.

From a completely microscopic point of view, it appears impossible at present to predict $T_a$ for $^3$He concentrations outside the s-wave regime, which is roughly $x_3 < 10^{-3} [19, 20]$. To provided some comparison with the present results, we have carried out numerical calculations of $D_\perp$ and $\mu M_0$ using an effective quasiparticle scattering “potential” $V(q)$, along the lines of Ref. $[8]$. Details of these calculations, which must be regarded as semi-phenomenological, will be reported elsewhere $[23]$ and only the results are given here. Using the $V(q)$ proposed in Ref. $[24]$, the calculated $\mu M_0$ for $T \rightarrow 0$ crosses zero at $x_3 = 3.65\%$, close to the experimental $x_c$ (Fig. $[8]$). At this $x_3$ (and in fact nearly independent of $x_3$), the calculated anisotropy temperature is $T_a = 3.7$ mK. Thus, the calculation predicts that the anisotropy temperature retains its s-wave value for $x_3$ far outside the s-wave regime, in agreement with the present experiments. Unlike $T_a$ the diffusion coefficients $D_{\parallel,\perp}$ and the spin rotation parameter $\mu M_0$ calculated from $V(q)$ are drastically modified from their s-wave values for this same range of concentrations; they agree well with our experimental values. As shown in Fig. $[4]$, the calculations predict a temperature variation for $\mu M_0/D_\perp$ over the range $2-30$ mK that is similar in magnitude to the variation observed experimentally. However, the calculated variation is approximately quadratic in temperature, unlike the linear variation seen experimentally. This is the only significant discrepancy we find between the experimental results presented here and these calculations based on $V(q)$.

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