Observation of Field-Induced Spin-Current Relaxation in a Fermi Liquid

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We have studied NMR spin echoes in ^{3}He liquid in a magnetic field $B_0=8$ T for temperatures $T\geq 4.5$ mK. The data are analyzed in terms of the Leggett-Rice effect to obtain the transverse spin-diffusion coefficient $D_\perp(T)$. For $T<20$ mK we find that $D_\perp$ is less than measured in earlier experiments at lower B_0. This phenomenon has been predicted for degenerate Fermi systems, due to the phase space created for quasiparticle scattering by spin polarization. The effect we have measured is more pronounced than suggested by scaling a dilute-gas theory result by a Fermi-liquid factor.

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In degenerate Fermi liquids in which interparticle collisions dominate scattering (^{3}He and certain metallic systems), the transport coefficients diverge as the temperature $T\rightarrow 0$. This fundamental property is due to the restriction of scattering phase space to a shell of width k_B about the Fermi surface. Recently, it was independently predicted by Meyerovich [1] and by Jeon and Mullin [2] that the divergence in the transverse spin-diffusion coefficient $D_\perp\propto T^{-2}$ is removed by arbitrarily small spin polarization P of the system. Below a temperature T_a which depends upon P, spin diffusion becomes anisotropic, with $D_\perp<D_\parallel$, and $D_\perp$ is predicted to have a finite value at zero temperature [3]. We report the first clear experimental evidence for this effect.

The effect is predicted because spin polarization opens a gap between spin-up and spin-down Fermi surfaces, which provides phase space for scattering that can relax transverse spin currents. By equating the energy gap in a magnetic field B_0 with the thermal energy at $T=T_a$ one estimates $T_a\sim\hbar\gamma B_0/k_B$, where γ is the gyromagnetic ratio. For ^{3}He in a strong laboratory field, $B_0=8$ T, the estimate is $T_a=12.4$ mK, but an earlier experiment [4] in which $D_\perp$ was measured at $B_0=8$ T and $T\geq 6$ mK found no significant deviation from either the expected low-field behavior or the measured behavior [5] of $D_\parallel$ at $B_0=9.2$ T. These earlier experiments used very dilute ^{3}He-^{4}He mixtures in which the ^{3}He quasiparticles form a weakly interacting gas. Thus, if polarization does cause $D_\perp<D_\parallel$, this must occur at lower temperatures or higher fields.

Reason to expect a lower value for T_a has come from the kinetic-equation calculations of Jeon and Mullin [2]. For a dilute, weakly polarized Fermi gas with s-wave interactions, they obtained $T_a=\hbar\gamma B_0/2\pi k_B$. Unfortunately this suggests spin-diffusion anisotropy should be difficult to observe in available laboratory fields unless nuclear demagnetization were used to achieve much lower temperatures.

In an attempt to observe the effect using conventional dilution refrigeration, we have studied spin diffusion in pure ^{3}He liquid at $B_0=8$ T. Pure ^{3}He is a strongly interacting system, but for $T\ll T_F$ it is successfully described by Fermi-liquid theory as a weakly interacting quasiparticle gas with strong mean-field effects. At zero pressure $T_F=1.8$ K and mean-field effects enhance the effective magnetic field by a factor of $(1+F_0^a)^{-1}=3.3$, where F_0^a is a Fermi-liquid factor [6]. To the extent that the effective field produces the same physical effects as a true field, the anisotropy temperature T_a might be enhanced by the same factor. This idea based on dilute-system theory must be considered a qualitative estimate, serving to motivate the experiment described here.

Our experimental data (Fig. 1) indicate that $D_\perp$ deviates from values measured in low field, for temperatures below 20 mK. These results were obtained by measuring NMR spin echoes in the presence of a gradient in B_0 of

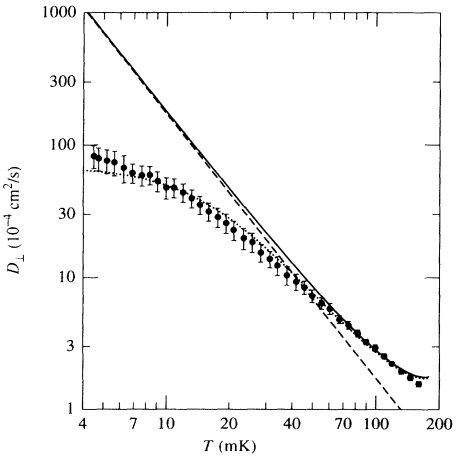

FIG. 1. Transverse spin-diffusion coefficient $D_\perp$ measured in ^{3}He at saturated vapor pressure, in a magnetic field $B_0=8$ T (points with error bars). The dashed curve shows a T^{-2} temperature dependence, while the solid curve contains a spin-fluctuation term. Earlier experiments demonstrated that $D_\perp$ follows the solid curve for $T=1$–100 mK at low field. The high-field data shown here fall below this curve for $T<20$ mK. The dotted curve is a fit with a simple model described in the text.

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$G = 16.0 \pm 0.5$ G/cm. The ^{3}He sample was contained and cooled by a cell similar to that described in Ref. [4]. The main chamber of the cell contained a vibrating-wire viscometer and a sintered silver heat exchanger coupled to the dilution refrigerator. An epoxy tube extended from the main chamber into the 260 MHz NMR resonator. A vacuum gap isolated the tube from the resonator, which was maintained at a much warmer temperature (800 mK). The active NMR region consisted of a 1.27 mm diam × 1.27 mm cylindrical chamber at the end of the epoxy tube, which was connected to the main chamber by a 0.36 mm diam × 5.7 mm channel.

A large temperature difference between sample and thermometer could mimic the effect reported here. The primary thermometer was a ^{3}He melting-pressure thermometer (MPT) thermally linked to the sample-cell heat exchanger and calibrated using the scale of Ref. [7]. The MPT was used to calibrate the vibrating-wire viscometer in the main sample chamber as a secondary thermometer. As both the temperature and polarization dependence of the viscosity of ^{3}He are known [8], it was possible to extrapolate the viscometer temperature scale to lower T. In this way the high accuracy of the MPT for $T \sim 100$ mK was extended to the lowest temperatures achieved, and the temperature of the ^{3}He in the main chamber was directly measured with no intervening thermal impedance. Although a heat leak directly into the NMR chamber could elevate its temperature above that measured by the viscometer, two arguments suggest that this was not the case. First, the thermal conductivity of ^{3}He varies as T^{-1}, so a heat leak into the NMR chamber would lead to a constant multiplicative error in the temperature scale rather than the leveling off seen in Fig. 1. Second, the heat leak required at the lowest temperature would be inconsistent with the small temperature offset (140 μK) observed between the viscometer and the MPT.

Measurements were made using a $[\phi]$-$\tau/2$-[180°] NMR pulse sequence, where $[\phi]$ denotes a pulse that tips the magnetization through an angle ϕ and $\tau/2$ is the time delay between the two pulses. Leggett [9] computed the amplitude h and phase θ of the resulting spin echo as

$$\ln h - \delta(1-h^2) = -\frac{D_\perp \gamma^2 G^2 \tau^3}{12[1+(\Omega\tau_\perp \cos\phi)^2]}, \qquad \theta = -\Omega\tau_\perp \cos\phi |\ln h| , \tag{1}$$

where $\delta = (\Omega\tau_\perp \sin\phi)^2/2[1+(\Omega\tau_\perp\cos\phi)^2]$. The relaxation time $\tau_\perp$ is related to the transverse spin-diffusion coefficient via $D_\perp = v_F^2(1+F_0^a)\tau_\perp/3$, where v_F is the Fermi velocity and Ω is a molecular-field rotation frequency proportional to P. In terms of the Larmor frequency ω_0 corresponding to P and Fermi-liquid parameters it is $\Omega = -\lambda\omega_0$, $\lambda = (1+F_0^a)^{-1} - (1+F_1^a/3)^{-1}$.

The deviations in h and θ caused by nonzero $\Omega\tau_\perp$ are called the Leggett-Rice (LR) effect. When $\Omega\tau_\perp \geq 1$ the spin-echo amplitude is strongly modified by the LR effect and Eq. (1) must be used to determine $D_\perp$. For ^{3}He at $B_0 = 8$ T, extrapolation of earlier low-field data gives $\Omega\tau_\perp \approx [(36\ \text{mK}/T]^2$ for temperatures $T \gg T_a$. As T_a is found in the present experiment to be well below 36 mK, a strong LR effect occurs at all temperatures $T < T_a$ for which spin-diffusion anisotropy might be observable. This is unavoidable with presently available B_0 fields, if as expected $T_a \propto B_0$ and $\Omega \propto B_0$. As Eq. (1) was derived from a macroscopic kinetic equation [9] that did not include zero-temperature spin-current relaxation, it will be important to reexamine this equation for significantly polarized systems.

An early experiment [10] that used spin echoes to measure $D_\perp$ in the presence of the LR effect gave anomalous results that were not confirmed by more recent work [4]. We propose here a possible explanation for those results. The analysis of Ref. [9] for a $[\phi]$-$\tau/2$-[180°] experiment shows that the spin current has a spatially uniform component parallel (in spin space) to the static field $\mathbf{B}_0$ and proportional to $\sin\phi$. This current has no effect for an infinite sample, but it eventually destroys the uniformity of the magnetization along $\mathbf{B}_0$ for a finite sample, invalidating Eq. (1). For the data reported here we have reduced its effect by using a small tipping angle $\phi = 10.2°$. In Ref. [10], $\phi = 45°$ and 90° were used. In a separate series of measurements we have varied ϕ, and found that the apparent value for $D_\perp$ decreases for large ϕ when $\Omega\tau_\perp > 1$.

In the present experiment both the amplitude and phase of the spin echoes were measured and they were simultaneously fitted by Eq. (1). The phase shift θ is due to molecular-field rotation, and so probes the magnetization. For each temperature the fit yields in addition to $D_\perp$ the independent quantity $D_\perp/\lambda\tau_\perp$. Figure 2 shows this fit for one temperature, and Fig. 3 shows the $D_\perp/\lambda\tau_\perp$ results versus temperature. As $T \to 0$ this quantity tends to a constant, as expected, and the value is in reasonable agreement with an earlier low-field measurement [11] also shown in Fig. 3. This agreement, as well as the observed proportionality of θ to τ^3 (Fig. 2), implies that the magnetization component along $\mathbf{B}_0$ remains constant over the duration of the experiment. Over this time period, the echo amplitude decays much faster than it would if $D_\perp$ equaled its low-field value, as shown by the dotted curve in Fig. 2. Note that a faster echo decay implies a smaller diffusion coefficient at this temperature, due to the LR effect.

Low-field experiments [12] observed deviations at *high* temperatures from $D_\perp \propto T^{-2}$, which are explained as an effect of spin-fluctuation exchange. The leading-order correction is $(D_\perp T^2)^{-1} = A(1 - T/T_{SF})$, where A and T_{SF} are constants [13]. We have fitted the data to the following model, which includes this correction. Polarization is assumed to create collisional phase space that simply adds to the relaxation rate, $\tau_\perp^{-1}(P,T) = \tau_\perp^{-1}(0,T) + f(P)$. In addition, we neglect the polarization dependence of $D_\perp/\tau_\perp$. Defining T_a as the temperature at

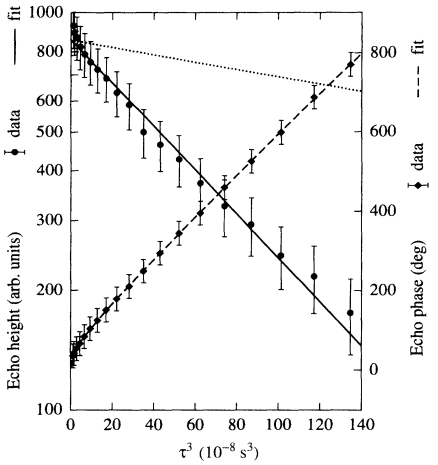

FIG. 2. Spin-echo amplitude and phase versus the cube of the echo delay time τ, measured at $T=6.87$ mK. The solid and dashed curves show a simultaneous least-squares fit of both quantities by Eq. (1) in the text. Note that the echo amplitude is plotted on a logarithmic scale. Both the amplitude and phase should appear as straight lines on this type of plot for small tipping angle ϕ. The initial curvature in the phase data and fit is due to a small instrumental frequency offset. The initial curvature in the amplitude data is probably due to ^{3}He in the channel connecting the NMR cell to the main cell, which gives a small echo that rapidly dephases. The dotted curve shows the amplitude decay that would be expected if $D_\perp$ were equal to its low-field value at this temperature.

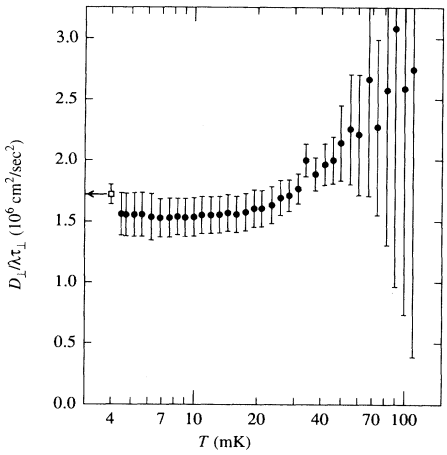

FIG. 3. Spin-rotation parameter versus temperature (circles). The square shows the result of an earlier low-field experiment [11] at $T\approx 1$ mK. For sufficiently low temperatures and polarizations this quantity should be both field and temperature independent. At higher temperatures $T\geq 50$ mK spin-rotation effects are small and the uncertainties become large.

which an unpolarized system has the same $D_\perp$ as the polarized system has at $T=0$ we obtain

$$D_\perp^{-1}=A[T^2(1-T/T_{SF})+T_a^2(1-T_a/T_{SF})]. \quad (2)$$

Stamp [14] discussed the modification of the spin-fluctuation correction in a spin-polarized system. This is not included in our model, but for $D_\perp$ it is expected to be overwhelmed by relaxation time anisotropy. The dotted curve in Fig. 1 shows a least-squares fit of the data by Eq. (2). We find $A=(5.8\pm 0.8)\times 10^5$ sec/cm^{2}K^2, $T_{SF}=257\pm 35$ mK in agreement with the low-field experiments [12].

The new effect we observe is quantified by the anisotropy temperature T_a. The fit result, $T_a=16.4\pm 2.2$ mK, is larger than the value (6.5 mK) obtained by multiplying the dilute-gas result of Ref. [2] by $(1+F_0^a)^{-1}$. This is not surprising, given the crudeness of this estimate, and it may indicate that the quasiparticle scattering amplitude for ^{3}He favors the phase space created by polarization more than does the s-wave scattering used for the calculation. Alternatively, proper incorporation of Fermi-liquid effects may well require more than the simple scaling of T_a proposed here [15]. A third possibility is that Eq. (2) is not a suitable quantitative model and that T_a is actually smaller than the fit value. This would be consistent with the systematic deviations visible in Fig. 1 (which, however, are within the error bars).

Despite considerable recent theoretical work on transverse spin dynamics in polarized systems [15,16], results that can be compared directly with the present experiment are not yet available. Although liquid ^{3}He is a strongly interacting system, there is a hierarchy of energy scales that may make quantitative calculations possible. The enhanced Zeeman energy $\hbar\gamma B_0/(1+F_0^a)$ is much smaller than the Fermi energy, and the polarization due to $B_0=8$ T is small, $P=0.017$. Thus, the quasiparticle structure and scattering amplitude are only weakly perturbed by such a field. A similar hierarchy of energy scales permits calculations for the superfluid phase of ^{3}He in terms of normal-state quasiparticle properties [6]. It is hoped that the experimental results presented here will stimulate the calculation of spin transport in slightly polarized ^{3}He using more realistic approximations to the scattering amplitude, such as the s-p approximation [6].

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