Spin transport in polaronic and superfluid Fermi gases

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Abstract. We present measurements of spin transport in ultracold gases of fermionic ⁶Li in a mixture of two spin states at a Feshbach resonance. In particular, we study the spin-dipole mode, where the two spin components are displaced from each other against a harmonic restoring force. We prepare a highly imbalanced, or polaronic, spin mixture with a spin-dipole excitation and we observe strong, unitarity-limited damping of the spin-dipole mode. In gases with small spin imbalance, below the Pauli limit for superfluidity, we observe strongly damped spin flow even in the presence of a superfluid core. This indicates strong mutual friction between superfluid and polarized normal spins, possibly involving Andreev reflection at the superfluid–normal interface.

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1. Introduction

The quality of transport is one of the most important properties distinguishing states of matter. Of great technical importance, electrons in condensed matter materials can flow as currents or supercurrents, or be localized in an insulator, or even switch their state of conductivity through controllable parameters like an applied magnetic field. It is the task of many-body physics to develop models that may explain the observed transport properties in a system. Dilute atomic gases cooled to quantum degeneracy provide ideal systems for testing many-body theories. In particular, Feshbach resonances [1] in atomic Fermi gases allow experimental control over the strength of two-body interactions, giving access to the Bose–Einstein condensation to Bardeen–Cooper–Schrieffer superfluid (BEC–BCS) crossover regime [2, 3]. Transport properties have played an important role in characterizing strongly interacting Fermi gases in the BEC-BCS crossover, with the observation of hydrodynamic flow indicating nearly perfect fluidity [4, 5], the measurement of collective excitation frequencies probing the equation of state [6–8], and the observation of vortex lattices in rotating gases demonstrating superfluidity [9]. The first observations of spin transport in Fermi gases were obtained in the weakly interacting regime, and showed the onset of Pauli blocking of collisions [10], and the transition from collisionless to hydrodynamic behavior [11]. Spin excitations have also been observed in Fermi gases as long-lived spin waves near zero scattering length [12].

Here we study spin transport in strongly interacting two-component Fermi gases. Spin currents are strongly damped in such systems due to the high collision rate between opposite spin atoms: as two-body scattering does not conserve relative momentum, each scattering event on average reduces the net spin current [13]. At the Feshbach resonance, scattering is maximal, with a mean-free path between collisions of opposite spins that can be as short as one interparticle spacing—the smallest possible in a three-dimensional (3D) gas. Measurements of spin transport in strongly interacting Fermi gases with an equal number of atoms in two spin states were recently reported [14]. Interactions were shown to be strong enough to reverse spin currents, with two clouds of opposite spin almost perfectly repelling each other. The spin diffusivity was found to reach a lower limit of the order of $\bar{\hbar}/m$ at unitarity, the quantum limit of diffusion. Here, we consider the case where the number of atoms in the two states is unequal, and study spin transport in the polarized and phase-separated superfluid regimes. In highly polarized systems that remain non-superfluid down to zero temperature [15–17], spin currents are expected to become undamped due to Pauli blocking [18–20]. In this imbalanced regime, a high-frequency mode observed after a compressional excitation was interpreted as a weakly damped spin quadrupole (or breathing) mode [21]. The question of the damping properties of the spin excitation and its temperature dependence was left open. Spin transport properties of ultracold Fermi gases have been investigated theoretically most recently in [18–20], [22–24], allowing comparison between theory and experiment.

In section 2, we present measurements of the damping rate of spin excitations in highly polarized Fermi gases as a function of temperature. We show that damping is maximal at finite temperatures. In section 3, we study smaller spin polarizations, below the Pauli limit of superfluidity [15], just enough to reveal the presence of a superfluid core in the system. We show that the spin-dipole mode is strongly damped in the presence of the superfluid. In a partially polarized Fermi gas, damping of spin motion is expected to persist at low temperatures due to Andreev reflection [20].
2. Highly imbalanced Fermi gases

Fermi gases with resonant interactions can remain normal down to zero temperature if the spin imbalance exceeds the Pauli (or the Clogston–Chandrasekhar) limit [15, 16, 21, 25, 26, 39]. We refer to the spin state with the larger population of atoms as the majority, or spin-up state, and the state with fewer atoms as the minority, or spin-down state. Radio-frequency (RF) spectroscopy [17] on such systems confirms the quasi-particle picture [27–29] where minority atoms are dressed by the majority Fermi sea, forming a quasi-particle known as the Fermi polaron. The energy of a single polaron in a zero-temperature Fermi sea of spin-up atoms has been described using the effective Hamiltonian [18, 19, 30],

\[ H = -\alpha \mu_\uparrow + \frac{\mathbf{p}^2}{2m^*}, \]

where \( \mathbf{p} \) is the momentum of the polaron, \( m^* \) is the polaron effective mass, \( \mu_\uparrow \) is the local spin-up chemical potential and \( \alpha \) characterizes the polaron binding energy. The parameters \( \alpha \) and \( m^*/m \), where \( m \) is the bare mass of spin-up and spin-down fermions, have been measured experimentally [17, 21, 31, 32] and calculated theoretically [30], [33–35], giving \( \alpha = 0.62 \) and \( m^*/m \approx 1.2 \) at zero temperature.

We consider a mixture of \( N_\uparrow \) spin-up fermions and \( N_\downarrow \) spin-down fermions at temperature \( T \) with equal masses and resonant interactions, held in a spin-independent potential of the form

\[ V(\rho, z) = \frac{1}{2} m_\uparrow^2 \omega_z^2 z^2 + V_\rho(\rho), \]

where \( \rho^2 = x^2 + y^2 \). The spin-up (down) clouds have density \( n_{\uparrow(\downarrow)}(\mathbf{r}) \) at position \( \mathbf{r} \). The minority cloud is initially displaced by a small amount \( Z_\downarrow(0) \) along the \( z \)-axis and is allowed to relax to its equilibrium position.

In the limit \( N_\downarrow \ll N_\uparrow \), the motion of the spin-up cloud due to momentum absorbed from the spin-down cloud may be neglected. The equation of motion of the spin-down center of mass \( Z_\downarrow \) is then [18]

\[ m^* \ddot{Z}_\downarrow + (1 + \alpha) m_\uparrow \omega_z^2 Z_\downarrow + \frac{m^*}{N_\downarrow} \int d^3r \, n_\downarrow(\mathbf{r}) \frac{v_\downarrow(\mathbf{r})}{\tau_p(\mathbf{r})} = 0, \]

where the factor of \( (1 + \alpha) \) is due to the attraction of the minority fermions to the majority cloud, \( 1/\tau_p \) is the local momentum relaxation rate due to collisions [18] and is equivalent to the spin drag coefficient [13, 22], and \( v_\downarrow \) is the local drift velocity of spin-down atoms. By dimensional analysis, \( \hbar/\tau_p(\mathbf{r}) \) must be given by the local majority Fermi energy times a universal dimensionless function of the local reduced temperature \( T / T_{\uparrow F\uparrow}(\mathbf{r}) \) and the local ratio \( T_{\downarrow F\downarrow}(\mathbf{r}) / T_{\uparrow F\uparrow}(\mathbf{r}) \) of the Fermi temperatures, where \( T_{\downarrow F\downarrow}(\mathbf{r}) \) is the local majority (minority) Fermi temperature. The first two terms in (3) follow from (1), (2) and the local density approximation, while the third term is due to damping and is not captured in (1). Equation (3) neglects a possible back-action of the minority on the majority atoms that might deform the majority density profile.

In our experimental realization of this transport problem, we use a gas of ultracold fermionic \(^6\text{Li} \) atoms. The \(^6\text{Li} \) atoms are cooled sympathetically with \(^{23}\text{Na} \) [36] and loaded into a hybrid optical and magnetic trap with an adjustable bias magnetic field [37]. The magnetic field curvature provides essentially perfect harmonic confinement along the axial (\( z \)) direction, while the optical dipole trap (laser wavelength 1064 nm, waist 115 \( \mu \text{m} \)) provides trapping in the radial
directions, with negligible contribution to the axial confinement. With this system, we perform a collection of time series measurements. In each time series, we prepare the system in a chosen initial state and observe its evolution.

At the Feshbach resonance at 834 G, the magnetic moments of ‘spin-up’ and ‘spin-down’ atoms, the two lowest hyperfine states of $^6$Li, are equal to 1 part in 1000, since their electron spin is in fact aligned with the magnetic field. Inducing a spin current is therefore extremely challenging on resonance. However, at lower fields, their magnetic moments differ, allowing separation of the two gas clouds by a magnetic field gradient. Our experimental procedure for producing these separated clouds is as follows.

We prepare the system starting with about $1 \times 10^7$ atoms of $^6$Li in the lowest hyperfine state, at a total magnetic field of 300 G. A small fraction of atoms are transferred to the second-lowest hyperfine state using a RF Landau–Zener sweep. The mixture is then evaporatively cooled for a variable amount of time by lowering the depth of the optical dipole trap from $k_B \times 7 \mu$K to a variable final depth between $k_B \times 0.5 \mu$K and $k_B \times 1 \mu$K, where $k_B$ is the Boltzmann constant. The optical dipole trap depth is then raised to $k_B \times 6 \mu$K, where the zero-temperature Fermi energy in the majority state is between $k_B \times 0.8 \mu$K and $k_B \times 1.3 \mu$K.

After the spin mixture is prepared at 300 G, the total magnetic field is reduced gradually over 500 ms to 50 G, where the ratio of the magnetic moments of the two states is 2.5 and interactions are very weak. A magnetic field gradient is applied along the $z$-direction for about 4 ms, imparting a linear momentum of the same sign but a different magnitude to each spin state. The clouds are then allowed to evolve for about 30 ms, and they execute about half of an oscillation period at different amplitudes and frequencies (the frequency ratio is 1.6 between spin-up and spin-down). When the clouds have returned to the center of the trap, their centers of mass are displaced from each other by about 200 $\mu$m (for comparison, the $1/e$ radius of the majority cloud in the $z$-direction is between 200 and 300 $\mu$m at this point). A second gradient pulse is applied along the same direction to remove the relative velocity of the two clouds. The second pulse also removes most of the total center-of-mass motion. The total magnetic field is then ramped to the Feshbach resonance at 834 G in about 5 ms. At resonance, the two spin states have identical trapping frequencies of 22.8 Hz.

To reach low temperatures, we apply a variable amount of evaporative cooling by lowering the depth of the optical dipole trap after reaching 834 G. The time available for evaporative cooling is limited to about 0.4 s by the relaxation time of the spin excitation. To reach high temperatures, we prepare a hotter cloud at 300 G and heat the system further at 834 G by releasing the atoms from the optical dipole trap and recapturing them. The depth of the optical dipole trap is then ramped gradually to a final value in 80 ms. The final depth is chosen to keep the number of atoms and the temperature approximately constant during the subsequent evolution, and it corresponds to an effective radial trap frequency ranging from 80 Hz for the low-temperature data to 250 Hz for the high-temperature data. After preparing the system at the chosen temperature and with a nonzero spin-dipole moment, we are left with typically $N_\uparrow \approx 4 \times 10^5$ atoms in the majority state and $N_\downarrow \approx 4 \times 10^4$ atoms in the minority state. We then allow the system to evolve for a variable wait time $t$ before measuring the densities of the spin-up and spin-down clouds using resonant absorption imaging. Note that we limit the

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2 The system as a whole oscillates harmonically along the $z$-direction at 22.8 Hz due to the residual center-of-mass energy. This motion does not affect the dynamics in the total center-of-mass frame because the trapping potential is harmonic in the $z$-direction, and therefore, according to Kohn’s theorem, the dynamics in the total center-of-mass frame are equivalent to the dynamics of a system at rest [38].
Figure 1. Measuring the spin-dipole mode of a highly polarized Fermi gas. (a) and (b) show 2D column density images of the minority and majority spin state, respectively, obtained using resonant absorption imaging in one run of the experiment. The imaging pulses are each 4 µs in duration and separated by 6 µs. The distance between the centers of mass in (a) and (b) is 34 µm. (c) Density of the majority (solid red circles) and minority (open blue circles) versus the effective potential energy \( V_{\text{eff}} \) defined in the text, obtained from the images in (a) and (b). The temperature of the cloud is found by fitting the non-interacting Fermi gas equation of state (solid line) to the region of the majority density where the minority fraction is 5% or less. (d) Displacement \( d \) of the minority center of mass relative to the majority center of mass as a function of time \( t \). This time series includes the run displayed in (a–c). Error bars are from fitting uncertainty (one std. dev.). The curve shows an exponential fit.

population of the majority cloud to ensure that the central optical density is less than 2, allowing for accurate density measurements.

Figures 1(a) and (b) show typical 2D column densities of the two spin states after evaporative cooling on resonance. From the column densities, we reconstruct the 3D densities \( n_\sigma(\rho, z) \) of each state \( \sigma = \uparrow, \downarrow \) using the inverse Abel transformation. The temperature of the system is determined by fitting the majority density as a function of potential energy to the equation of state of a non-interacting Fermi gas [37] (figure 1(c)): \( n_{\uparrow, \text{FG}} = -\lambda^{-3} \zeta_{3/2} (\exp(\mu - V_{\text{eff}}) - 1) / \pi \), where \( \lambda = \sqrt{2\pi \hbar^2 / mk_B T} \) is the thermal de Broglie wavelength, \( \beta = 1 / k_B T \), the fit parameters are the chemical potential \( \mu \) and the temperature \( T \), \( \zeta_{3/2} \) is the polylogarithm of order 3/2, and \( V_{\text{eff}} = V(\rho, z - Z_\uparrow) \) is the effective potential energy. The fit is restricted to \( z < Z_\uparrow \) and to the outer edges of the majority cloud, where \( n_\downarrow / n_\uparrow < x_c \). We used a cut-off minority fraction of \( x_c = 0.05 \) for all clouds with \( T < 0.5T_{F\uparrow} \). For some of the data with \( 0.5 < T / T_{F\uparrow} < 1 \), \( x_c \) was increased to 0.08 to increase the available signal, while for the data with \( T > 2T_{F\uparrow} \), \( x_c \) was increased to 0.15 for the same reason. These increases in \( x_c \) should not affect the accuracy of the thermometry because the system interacts less strongly at high \( T / T_{F\uparrow} \) [3]. This is demonstrated by our spin susceptibility measurements for the balanced case in [14] that agree with the compressibility above \( T / T_F \approx 1 \), showing the absence of spin correlations in this temperature regime. For normalization, the central densities \( n_\sigma(0) \) of each species are recorded and used to define the central Fermi energies \( E_{\text{FG}} = \hbar^2 k_{\text{FG}}^2 / 2m_\sigma \), with \( k_{\text{FG}} = (6\pi^2 n_\sigma(0))^{1/3} \), \( m_\uparrow = m \), and \( m_\downarrow = m^* \), and Fermi temperatures \( T_{\text{FG}} = E_{\text{FG}} / k_B \).

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Spin transport is measured by observing the time evolution of the center-of-mass separation $d(t) = Z_1(t) - Z_2(t)$ (figure 1(d)), with $Z_{1,2}(t)$ the center of mass of the majority (minority) cloud along the $z$-axis at time $t$, determined from a 2D Gaussian fit to the column density. We find that $d$ relaxes exponentially to zero, corresponding to an overdamped spin-dipole mode, and fit the evolution to an exponential function $d(t) = d_0 e^{-t/\tau}$. We report the dimensionless relaxation time $\bar{\tau} = \hbar \omega_z^2 \tau / E_{F\uparrow}$. Equation (3) implies that $\bar{\tau}$ is mostly independent of the absolute scales set by the density and the trapping frequency. Defining the average momentum relaxation rate as

$$\bar{\tau}_P = \frac{\int d^3 r \ n_\downarrow(r) \bar{v}_\downarrow(r) / \tau_P (r)}{\int d^3 r \ n_\uparrow(r) \bar{v}_\uparrow(r)},$$

and making the approximation that $\bar{\tau}_P$ is constant in time relates $\bar{\tau}$ to fundamental properties of the system as

$$\bar{\tau} \approx \frac{m^*/m}{1 + \alpha} \cdot \frac{1}{\bar{\tau}_P} \cdot \frac{\hbar / E_{F\uparrow}}{\hbar / E_{F\downarrow}},$$

in the limit $(\omega_z \tau)^2 \gg 1$ realized in our measurements, where $\tau$ is always at least 100 ms, and so $(\omega_z \tau)^2 \gg 200$.

Figure 2 shows the measured values of the dimensionless relaxation time $\bar{\tau}$ as a function of the reduced temperature $T / T_{F\uparrow}$. $\bar{\tau}$ increases at low temperatures before reaching a maximum of $0.13(3) E_{F\uparrow}$ for $T / T_{F\uparrow} = 0.40(6)$, and decreases at higher temperatures. We interpret the behavior of the relaxation time at low temperatures as a consequence of Pauli blocking: as the temperature is lowered significantly below the majority Fermi temperature, the phase space available for a minority atom to scatter goes to zero. The reduction in $\bar{\tau}$ at high temperatures is expected: at high temperatures, $1/\bar{\tau}_P$ is essentially given by the collision rate in the gas [40], $1/\bar{\tau}_P \sim n \sigma v$. The scattering cross-section $\sigma$ on resonance for $T \gg T_{F\uparrow}$ is given by the square of the de Broglie wavelength and is thus proportional to $1/T$, while the average speed $v$ of the particles is proportional to $\sqrt{T}$. Hence, $\bar{\tau}$ is expected to decrease like $\hbar n \sigma v / E_{F\uparrow} \propto \sqrt{T_{F\uparrow}/T}$. We observed behavior similar to figure 2 in 3D Fermi gases with resonant interactions and equal spin populations in [14], although we see more significant Pauli blocking here than in [14] at comparable temperatures.

The systematic uncertainties of the measured values have been estimated, and are comparable to or less than the statistical errors. The temperature measurement uses knowledge of the potential energy (2). The radial potential energy function $V_\rho(\rho)$ is assumed to have the form

$$V_\rho(\rho) = \frac{2aP}{\pi w_0^2} (1 - e^{-2\rho^2/w_0^2}) - \frac{m \omega_z^2 \rho^2}{4},$$

where $a$ is a known constant expressing the polarizability of the atoms, $P$ is the optical power of the dipole trap and $w_0$ is the waist of the trapping beam, and $\omega_z = 2\pi \times 22.8$ Hz is the axial trapping frequency. Direct measurements give $P$ and $w_0$ with 5–10% accuracy. To refine the trap model, we sum the 3D densities of the majority atom clouds for each value of $P$ used in the experiment, taking only $t > 190$ ms, and use the known axial potential together with the local density approximation to obtain $V_\rho(\rho)$. The model (6) is then fit to the experimentally measured $V_\rho(\rho)$ with $w_0$ as a free parameter, giving $w_0 = 115 \mu$m. Equivalently, $P$ could have been used as the free parameter; the difference in the two approaches adds less than 1% uncertainty to the potential energy. The uncertainty in the potential energy is dominated by noise in the images of
Figure 2. Normalized relaxation time of the spin-dipole mode of a highly polarized Fermi gas as a function of the reduced temperature $T/T_{F\uparrow}$. $T_{F\uparrow}$ is the local Fermi temperature at the center of the majority cloud. The solid curve is the low-temperature limit from [18], given by equation (7). The dashed curve is the expression $0.08 \sqrt{T_{F\uparrow}/T}$. The inset shows the average ratio of the minority cloud size to the majority cloud size as a function of the reduced temperature $T/T_{F\uparrow}$. The cloud sizes are defined as the $1/e$ radii along the $z$-axis, estimated by fitting a 2D Gaussian function to the column densities of the two spin states. In both figures, each point is a weighted average of the results from 1 to 3 time series, with each time series containing on average 30 spin-up–spin-down image pairs. The error bars give standard deviations due to statistical fluctuations within a time series. Where the results of more than one time series are averaged, the error bars show the standard deviation of the weighted mean, determined from the standard deviations from each time series.

the clouds, giving an uncertainty in $w_0$ of about 2 $\mu$m. This implies a 7% systematic error on the potential energy at $\rho = 40$ $\mu$m (a typical value of $\rho$ in the outer region of the cloud). The resulting systematic uncertainty on the temperature is 10% at the lowest temperatures, and 5% for temperatures near $T_F$ or higher. Measurements of density are affected by the laser linewidth, imperfect polarization of the imaging light, and nonlinearities from saturation of the imaging transition, Doppler shifting of atoms scattered by the imaging light and pumping into transparent final states. The density measurement is calibrated using equilibrium low-temperature clouds with large spin imbalance. The systematic uncertainty in the density is 10%. This leads to a total systematic error in the reduced temperatures of 8–12%, and a systematic error in $\tilde{\tau}$ of 6%. The magnification of the imaging system is calibrated to 0.5% and does not contribute significantly to the uncertainties in $w_0$ or $d$.

It would be interesting to have available a calculation of spin transport coefficients such as $1/\tau_P$ at arbitrary temperatures for comparison with our data. A full solution is available for Fermi gases with equal populations in one spatial dimension [22, 23] and shows qualitative features similar to our data, with a maximum of the spin drag coefficient (analogous to $\tilde{\tau}$) at finite temperatures of the order of $T_F$.

We expect our data to differ quantitatively from predictions for a homogeneous system. The measured quantity $\tilde{\tau}$ is a global property of the trapped system, while the momentum relaxation
rate $1/\tau_p$ is a local quantity. For $T \gg T_{F\uparrow}$, $1/\tau_p \propto n_\uparrow$, and $1/\tau_p$, increases with increasing majority density, while for $T \ll T_{F\uparrow}$, due to Pauli blocking $1/\tau_p \propto E_{F\uparrow}(T/T_{F\uparrow})^2 \propto n_\uparrow^{-2/3}$, and $1/\tau_p$ decreases with increasing majority density. Additionally, the variation in $1/\tau_p$ should cause the spin current to be non-uniform. The effect of inhomogeneity should be greater at high reduced temperatures, where the minority cloud size approaches the majority cloud size. The inset in figure 2 shows the ratio of the cloud sizes $R_\downarrow/R_\uparrow$ as a function of the reduced temperature, where $R_\uparrow(\downarrow)$ is the $1/e$ width in the $z$-direction from a 2D Gaussian fit to the majority (minority) column density. Indeed, $R_\downarrow/R_\uparrow$ increases with increasing $T/T_{F\uparrow}$. Even at the lowest temperatures, $R_\downarrow/R_\uparrow$ remains significant, attaining a value of 0.7, due to the finite minority fraction $N_\downarrow/N_\uparrow \approx 0.1$. The effect of inhomogeneity is therefore reduced at low temperatures, but should remain present.

We compare our results for $\bar{\tau}$ at low temperatures to the low-temperature limit in [18], which can be written as

$$\frac{1/\tau_p(0)}{E_{F\uparrow}/\hbar} = c \frac{\alpha^2}{1 + \alpha} \left( \frac{m^*}{m} \right)^2 \left( \frac{T}{T_{F\uparrow}} \right)^2,$$

for temperatures $T \ll T_{F\uparrow}$.

The prefactor $c$ changes slightly from $c = \frac{2m^3}{3} = 6.89 \ldots$ to $c \approx 6.0$ as the temperature rises from far below $T_{F\uparrow}$, where even the minority cloud is in a classical gas [18]. In our coldest data, $T \approx 0.5T_{F\uparrow}$ and $T_{F\downarrow} \approx 0.3T_{F\uparrow}$, assuming $m^* = 1.2m$. To compare our data with [18], using (7), we set $c = \frac{2m^3}{3}$, $\alpha = 0.6$ and $m^* = 1.2m$. The comparison is affected by the inhomogeneous trapping potential in the experiment, as equation (7) gives the local value of $1/\tau_p$ at the center of the majority cloud. The experimental data agree with the value from equation (7) at the lowest temperatures measured (see figure 2). The deviation at higher temperatures is expected as the $T \ll T_{F\uparrow}$ limit becomes inapplicable. The convergence of the experimental data to the theoretical value at low temperature despite the inhomogeneity of the system may be partly due to the reduced minority cloud size at low temperatures, which reduces the effects of inhomogeneity, as discussed above. Additionally, the variation in the momentum relaxation rate with density will to some extent cancel at moderately low temperatures, as $1/\tau_p$ changes from increasing with increasing density at high reduced temperatures to decreasing with increasing density due to Pauli blocking at low reduced temperatures. The crossing of the experimental curve with the predictions for a uniform system at low temperatures therefore does not necessarily indicate that the inhomogeneity is negligible at low temperatures in this measurement.

At high temperatures $T \gg T_{F\downarrow,\uparrow}$, the spin transport properties of a trapped system can be calculated from the Boltzmann transport equation. For vanishing minority fraction, we find (now with $\alpha = 0$ and $m^* = m$ and assuming harmonic trapping in all three directions) [14]

$$\bar{\tau} = \frac{8}{9\pi^{3/2}} \frac{\epsilon}{\sqrt{T}} \frac{E_{F\uparrow}}{T} \approx 0.16 \frac{\epsilon}{\sqrt{T}} \frac{T_{F\uparrow}}{T}, (8)$$

where $\epsilon = 1$ when the minority drift velocity distribution $v_\downarrow$ is uniform. This result features the expected dependence $\propto \sqrt{\frac{T_{F\uparrow}}{T}}$ on temperature. The relative velocity between the two spin states

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3 We omit a term due to the relative velocity of the spin up and spin-down clouds, which produces a correction of less than 1% in the overdamped, finite-temperature regime accessed in this experiment.
cannot be truly constant in space but has to be depressed in the center, where the density is highest and the momentum relaxation is fastest. In general,

\[ \epsilon = \frac{\int d^3r v_\downarrow(\frac{\vec{r}}{\sqrt{2}})e^{-\beta V}}{\int d^3r v_\downarrow(\vec{r})e^{-\beta V}}, \]

where \( V \) is the trapping potential (here assumed to be quadratic). For example, for a quadratic drift velocity profile, \( v_\downarrow(\vec{r}) = ax^2 + by^2 + cz^2 \), the predicted \( \tilde{\tau} \) is reduced by factor of \( \epsilon = 2 \). We find that the high-temperature result (8) with \( \epsilon = 2 \) leads to close agreement with our experimental results (figure 2). This model is interesting because it estimates the effects of inhomogeneous density and velocity distributions, but it has shortcomings. The drift velocity should remain non-zero everywhere, rather than going to zero at the origin as in the quadratic case, and should have a radial component. A full quantitative description of the overdamped spin-dipole motion in the high-temperature limit in an external trapping potential will therefore be more complex.

3. A superfluid with small spin polarization

We extend the method of the previous section to study spin transport in Fermi gases with resonant interactions and small spin imbalance. When the global polarization \( \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \) is less than about 75\% in a harmonically trapped Fermi gas at low temperature and with resonant interactions, the system phase separates into a superfluid core surrounded by a polarized normal state region [15, 16, 21]. The superfluid core is visible as a sharp reduction in the density difference of the two spin states [16]. The transition between the superfluid and the imbalanced normal regions forms a sharp interface below a tricritical point, where the density imbalance jumps between the two regions [39]. Scattering and spin transport at the interface between a normal and superfluid Fermi gas have been considered theoretically in [20, 41].

To observe spin transport in an imbalanced gas containing a superfluid, we prepare a spin mixture with a global polarization of 17(3)\%. The gas is cooled at 300 G and again at 834 G after creating the spin-dipole excitation as described in the previous section. Two off-resonant phase contrast images are taken to measure the densities of each spin state. An imaging pulse tuned halfway between the resonance frequencies of the two states directly measures the difference in the column densities (figure 3(a)), while a second pulse, red-detuned from both states (figure 3(b)), provides additional information needed to reconstruct the total column density in each state [39]. From the column densities of each state, we obtain 3D density distributions using the inverse Abel transformation.

The 2D spin density (figure 3(a)) and 3D spin density (figure 3(c)) show a reduction near the center of the trap, with the 3D density going to zero, characteristic of the superfluid core in imbalanced Fermi gases [16]. We have checked that the shell structure remains even after the spin density reaches equilibrium. Additionally, we estimate the temperature \( T \) of the system to confirm that it is cold enough to contain a superfluid. In unpolarized systems, the superfluid transition is predicted to occur at about \( T_c / T_F = 0.173(6) \) [42], where \( k_B T_F = \hbar^2/(6\pi^2 n(0))^{3/2}/2m \) and \( n \) is the density per spin state. This theoretical value agrees well with a determination of \( T_c / T_F \) by our group. Fitting the equation of state of a unitary Fermi gas at zero imbalance [43] to the majority (minority) density gives an estimate \( T_{c(1)} \) of the temperature. The fits are restricted to \( V_{\sigma,eff} > 0.3 \mu K \), where \( V_{\sigma,eff} = V(\rho, z - Z_{\sigma}) \), to exclude

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**Figure 3.** Spin-dipole mode of an imbalanced Fermi gas with a superfluid core. Phase contrast images are taken with imaging light detuned (a) halfway between the resonance frequencies of the two states and (b) at large red detuning from both states. The image in (a) is proportional to the difference in column densities of the two states. The depletion of the density difference in the center of the cloud indicates the superfluid region. It is displaced from the center of the majority due to the spin-dipole excitation. Panel (c) shows the difference in reconstructed 3D densities of the spin up and spin-down clouds as a function of the $z$ coordinate for $z > 0$. The depletion in the center again indicates pairing and superfluidity [16]. An elliptical average over a narrow range of the radial coordinate $\rho$ is used to increase the signal-to-noise ratio. (d) The temperature is estimated from the 3D densities of the two states as a function of the effective potential $V_{\text{eff}}$ defined in the text. Solid red circles: majority density, open blue circles: minority density. The curves are fits to the densities using the equation of state of a unitary Fermi gas at zero imbalance to get upper and lower bounds on the temperature.

the putative superfluid region. Compared to a balanced gas at unitarity with $N_\uparrow' = N_\downarrow' = N_\uparrow$, and at the same temperature $T$, the majority cloud should have a larger size because the interaction energy between the spin-up and spin-down atoms is attractive. We therefore expect that $T_\uparrow$ is an overestimate of $T$. Likewise, we expect $T_\downarrow < T$, and we consider $T_\uparrow$ and $T_\downarrow$ to provide approximate upper and lower bounds on $T$.

Figure 4(a) shows the temperature bounds during the approach to equilibrium. Time-averaging gives $0.12(1) < T / T_F < 0.15(2)$, where $T_F \equiv T_{F\uparrow} \approx T_{F\downarrow}$. The error estimates include the standard error of the mean and the systematic error from uncertainty in the potential energy and in the density. These temperature bounds confirm that the system is in the vicinity of the superfluid transition.

Even in the presence of the superfluid core, we still observe strong damping of the spin-dipole mode. Figure 4(b) shows that the displacement $d$ between the majority and minority centers of mass along the $z$-axis relaxes gradually to zero, rather than oscillating as would be expected in a dissipationless system. The $1/e$ relaxation time $\tau = 360 \text{ ms}$ corresponds to a spin drag coefficient $[13, 22]$ of $\omega^2 \tau = 0.06(1) E_{F\uparrow} / \hbar$, close to the maximum spin drag coefficient in non-polarized trapped Fermi gases at unitarity [14].
Figure 4. (a) Reduced temperature as a function of time during relaxation of the spin-dipole excitation in a spin-polarized Fermi gas containing a superfluid region. Red solid (blue open) circles: $T_{T(\downarrow)} / T_{F\uparrow}$ from a fit to the edge of the majority (minority) spin state using the equation of state of an unpolarized unitary Fermi gas, giving an upper (lower) limit to true temperature. (b) The displacement of the spin-up and spin-down centers of mass relaxes exponentially, indicating strong spin drag despite the presence of a superfluid. Error bars: one std. dev. from fitting error.

The strong damping is reminiscent of the friction between the normal and superfluid component in liquid helium [44] and in atomic Bose–Einstein condensates [46]. In the latter case, out-of-phase oscillations between the condensate and the thermal component are strongly damped. Even at low temperatures, currents in superfluids as well as in 1D superconducting wires are still damped due to phase slips [46–48]. In the presented case of a partially polarized Fermi gas, Andreev reflection of unpaired atoms at the normal-to-superfluid interface should cause spin current decay even at the lowest temperatures [20, 41]. At higher temperatures or if the majority chemical potential in the normal state region can overcome the pairing gap, the microscopic velocity of majority atoms will significantly exceed the critical velocity of the superfluid of about $0.3v_F$ [49, 50], causing strong dissipation of spin currents. The relative importance of dissipation at the interface versus dissipation inside the superfluid could be determined by whether a spin current flows through the superfluid or around it. However, we are not able to determine the spatial distribution of the spin current with our current data.

4. Conclusions

In this work, we presented our measurements on the damping of the spin-dipole mode in a highly polarized Fermi gas with resonant interactions, over a wide range of temperatures. The damping is seen to become weaker at temperatures significantly less than the majority Fermi energy, as expected from Pauli blocking, i.e. the fact that quasi-particles in a Fermi liquid become long lived at sufficiently low temperatures. These measurements provide the first quantitative test of theoretical calculations of the spin transport properties of highly polarized Fermi gases. We also observe spin transport in a Fermi gas with low spin polarization containing a superfluid region. It is found that the spin-dipole motion remains strongly damped, revealing the importance of friction between the superfluid and the normal component, possibly accompanied by reflection processes at the interface.
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References

[1] Chin C, Grimm R, Julienne P and Tiesinga E 2010 Feshbach resonances in ultracold gases Rev. Mod. Phys. \textbf{82} 1225–86

[2] Ketterle W and Zwierlein M W 2008 Making, probing and understanding ultracold Fermi gases \textit{Ultracold Fermi Gases, Proc. Int. School of Physics ‘Enrico Fermi’, Course CLXIV (Varenna, 20–30 June 2006)} ed M Inguscio, W Ketterle and C Salomon (Amsterdam: IOS Press) pp 1–462

[3] Giorgini S, Pitaevskii L P and Stringari S 2008 Theory of ultracold atomic Fermi gases Rev. Mod. Phys. \textbf{80} 1215–60

[4] Cao C, Elliott E, Joseph J, Wu H, Petricka J, Schäfer T and Thomas J E 2010 Universal quantum viscosity in a unitary Fermi gas Science \textbf{331} 58–61

[5] O’Hara K M, Hemmer S L, Gehm M E, Granade S R and Thomas J E 2002 Observation of a strongly interacting degenerate Fermi gas of atoms Science \textbf{298} 2179

[6] Kinast J, Hemmer S L, Gehm M E, Turlapov A and Thomas J E 2004 Evidence for superfluidity in a resonantly interacting Fermi gas Phys. Rev. Lett. \textbf{92} 150402

[7] Bartenstein M, Altmeyer A, Riedl S, Jochim S, Chin C, Hecker-Denschlag J and Grimm R 2004 Collective excitations of a degenerate gas at the BEC-BCS crossover Phys. Rev. Lett. \textbf{92} 203201

[8] Altmeyer A, Riedl S, Kohstall C, Wright M J, Geursen R, Bartenstein M, Chin C, Hecker J Denschlag and Grimm R 2007 Precision measurements of collective oscillations in the BEC-BCS crossover Phys. Rev. Lett. \textbf{98} 040401

[9] Zwierlein M W, Abo-Shaeer J R, Schirotzek A, Schunck C H and Ketterle W 2005 Vortices and superfluidity in a strongly interacting Fermi gas Nature \textbf{435} 1047–51

[10] DeMarco B and Jin D S 2002 Spin excitations in a Fermi gas of atoms Phys. Rev. Lett. \textbf{88} 040405

[11] Gensemer S D and Jin D S 2001 Transition from collisionless to hydrodynamic behavior in an ultracold Fermi gas Phys. Rev. Lett. \textbf{87} 173201

[12] Du X, Luo L, Clancy B and Thomas J E 2008 Observation of anomalous spin segregation in a trapped Fermi gas Phys. Rev. Lett. \textbf{101} 150401

[13] D’Amico I and Vignale G 2000 Theory of spin Coulomb drag in spin-polarized transport Phys. Rev. B \textbf{62} 4853–7

[14] Sommer A, Ku M, Roati G and Zwierlein M W 2011 Universal spin transport in a strongly interacting Fermi gas Nature \textbf{472} 201–4

[15] Zwierlein M W, Schirotzek A, Schunck C H and Ketterle W 2006 Fermionic superfluidity with imbalanced spin populations Science \textbf{311} 492–6

[16] Shin Y, Zwierlein M W, Schunck C H, Schirotzek A and Ketterle W 2006 Observation of phase separation in a strongly interacting imbalanced Fermi gas Phys. Rev. Lett. \textbf{97} 030401

[17] Schirotzek A, Wu C-H, Sommer A and Zwierlein M W 2009 Observation of Fermi polaron in a tunable Fermi liquid of ultracold atoms Phys. Rev. Lett. \textbf{102} 230402–4

[18] Bruun G M, Recati A, Petchick C J, Smith H and Stringari S 2008 Collisions properties of a polarized Fermi gas with resonant interactions Phys. Rev. Lett. \textbf{100} 240406

[19] Recati A, Lobo C and Stringari S 2008 Role of interactions in spin-polarized atomic Fermi gases at unitarity Phys. Rev. A \textbf{78} 023633

New Journal of Physics \textbf{13} (2011) 055009 (http://www.njp.org/)
[20] Parish M M and Huse D A 2009 Evaporative depolarization and spin transport in a unitary trapped Fermi gas Phys. Rev. A 80 063605
[21] Nascimbène S, Navon N, Jiang K J, Tarruell L, Teichmann M, McKeever J, Chevy F and Salomon C 2009 Collective oscillations of an imbalanced Fermi gas: axial compression modes and polaron effective mass Phys. Rev. Lett. 103 170402–4
[22] Polini M and Vignale G 2007 Spin drag and spin-charge separation in cold Fermi gases Phys. Rev. Lett. 98 266403
[23] Rainis D, Polini M, Tosi M P and Vignale G 2007 Spin drag and spin-charge separation in cold Fermi gases Phys. Rev. Lett. 98 180402
[24] Duine R A, Polini M, Stoof H T C and Vignale G 2010 Spin drag in an ultracold Fermi gas on the verge of ferromagnetic instability Phys. Rev. Lett. 104 220403
[25] Clogston A M 1962 Upper limit for the critical field in hard superconductors Phys. Rev. Lett. 9 266
[26] Chandrasekhar B S 1962 A note on the maximum critical field of high-field superconductors Appl. Phys. Lett. 1 7
[27] Chevy F 2006 Universal phase diagram of a strongly interacting Fermi gas with unbalanced spin populations Phys. Rev. A 74 063628
[28] Combescot R, Recati A, Lobo C and Chevy F 2007 Normal state of highly polarized Fermi gases: simple many-body approaches Phys. Rev. Lett. 98 180402
[29] Prokof’ev N and Svistunov B 2008 Fermi-polaron problem: diagrammatic Monte Carlo method for divergent sign-alternating series Phys. Rev. B 77 020408
[30] Lobo C, Recati A, Giorgini S and Stringari S 2006 Normal state of a polarized Fermi gas at unitarity Phys. Rev. Lett. 97 200403
[31] Shin Y-I 2008 Determination of the equation of state of a polarized Fermi gas at unitarity Phys. Rev. A 77 041603
[32] Nascimbène S, Navon N, Jiang K J, Chevy F and Salomon C 2010 Exploring the thermodynamics of a universal Fermi gas Nature 463 1057–60
[33] Combescot R and Giraud S 2008 Normal state of highly polarized Fermi gases: full many-body treatment Phys. Rev. Lett. 101 050404
[34] Prokof’ev N V and Svistunov B V 2008 Bold diagrammatic Monte Carlo: a generic sign-problem tolerant technique for polaron models and possibly interacting many-body problems Phys. Rev. B 77 125101
[35] Pilati S and Giorgini S 2008 Phase separation in a polarized Fermi gas at zero temperature Phys. Rev. Lett. 100 030401
[36] Hadzibabic Z, Gupta S, Stan C A, Schunck C H, Zwierlein M W, Dieckmann K and Ketterle W 2003 Fifty-fold improvement in the number of quantum degenerate fermionic atoms Phys. Rev. Lett. 91 160401
[37] Zwierlein M W, Schunck C H, Schiroztek A and Ketterle W 2006 Direct observation of the superfluid phase transition in ultracold Fermi gases Nature 442 54–8
[38] Dobson J F 1994 Harmonic-potential theorem: implications for approximate many-body theories Phys. Rev. Lett. 73 2244
[39] Shin Y-I, Schunck C H, Schiroztek A and Ketterle W 2008 Phase diagram of a two-component Fermi gas with resonant interactions Nature 451 689–93
[40] Vichi L and Stringari S 1999 Collective oscillations of an interacting trapped Fermi gas Phys. Rev. A 60 4734
[41] Van Schaeybroeck B and Lazarides A 2007 Normal-superfluid interface scattering for polarized fermion gases Phys. Rev. Lett. 98 170402
[42] Goulko O and Wingate M 2010 Thermodynamics of balanced and slightly spin-imbalanced Fermi gases at unitarity Phys. Rev. A 82 053621
[43] Ku M, Schiroztek A, Sommer A, Zwierlein M, Van K Houcke, Werner F, Kozik E, Prokofev N and Svistunov B 2010 equation of state of a strongly interacting atomic Fermi gas, available at http://meetings.aps.org/link/BAPS.2010.DAMOP.W6.1
[44] Vinen W F 1957 Mutual friction in a heat current in liquid helium ii. iii theory of mutual friction Proc. R. Soc. A 242 493–515

New Journal of Physics 13 (2011) 055009 (http://www.njp.org/)
[45] Stamper-Kurn D M, Miesner H-J, Inouye S, Andrews M R and Ketterle W 1998 Collisionless and hydrodynamic excitations of a Bose–Einstein condensate Phys. Rev. Lett. 81 500–3
[46] Langer J S and Michael Fisher E 1967 Intrinsic critical velocity of a superfluid Phys. Rev. Lett. 19 560–3
[47] Langer J S and Ambegaokar V 1967 Intrinsic resistive transition in narrow superconducting channels Phys. Rev. 164 498–510
[48] McKay D, White M, Pasienski M and DeMarco B 2008 Phase-slip-induced dissipation in an atomic Bose–Hubbard system Nature 453 76–80
[49] Miller D E, Chin J K, Stan C A, Liu Y, Setiawan W, Sanner C and Ketterle W 2007 Critical velocity for superfluid flow across the BEC-BCS crossover Phys. Rev. Lett. 99 070402
[50] Combescot R, Kagan M Yu and Stringari S 2006 Collective mode of homogeneous superfluid Fermi gases in the BEC-BCS crossover Phys. Rev. A 74 042717