Observation of spin Coulomb drag in a two-dimensional electron gas: Supplementary online material

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Charge diffusion in the absence of spin Coulomb drag. In our paper, we compare experimental results for the spin diffusion coefficient, D_s, with the prediction of D'Amico and Vignale [Ref. 10],

$$D_s = \frac{\sigma_c}{e^2\chi_s}\frac{1}{1+ \mid \rho_{\uparrow\downarrow} \mid /\rho}. \tag{1}$$

We motivate this comparison by first estimating the value of D_s expected in the absence of spin Coulomb drag (SCD). Here we describe more fully how this quantity is estimated from the experimental data. A general expression for the spin diffusion coefficient, valid in the presence of interactions, is the Einstein relation, $D_s = \sigma_s/e^2\chi_s$, where σ_s and χ_s are the spin conductance and susceptibility, respectively. In the absence of SCD the spin and charge conductances are equal, and therefore $D_s = \sigma_c/e^2\chi_s$, the same expression as obtained by setting $\rho_{\uparrow\downarrow} = 0$ in Eq. 1. We can rewrite D_s in this limit as $\sigma_c/e^2 f\chi_0$, where the factor $f \equiv \chi_s/\chi_0$ expresses the enhancement of the spin susceptibility relative to the noninteracting susceptibility χ_0. Both analytical theory [Ref. 8] and Monte Carlo simulations [Ref. 9] indicate that the factor f is less than 1.4 in the range of electronic density spanned by our samples (and less than 1.25 for the highest-electronic-density sample). Therefore, the quantity $\sigma_c/e^2\chi_0$, which we define as D_{c0}, provides a reasonable approximation for the spin diffusion coefficient expected in the absence of SCD.

D_{c0} can be obtained directly from our 4-probe transport measurements, which determine σ_c, n, and therefore E_F. For a 2DEG, the noninteracting susceptibility χ_0 can be expressed in closed form in terms of the E_F, T, and the density of states, N_F, as we now describe. The starting point is the definition $\chi_0 \equiv \partial n/\partial\mu$, where the derivative of n with respect to chemical potential μ is for the noninteracting system. n and μ are related through the integral of the Fermi function,

$$n = N_F \int_0^\infty \frac{dE}{1 + e^{(E-\mu)/kT}}, \tag{2}$$

which can be evaluated analytically to obtain,

$$n = N_F k_B T \ln(1 + e^{\mu/kT}). \tag{3}$$

Taking the derivative of n with respect to μ yields the following expression for χ_0,

$$\chi_0 \equiv \frac{\partial n}{\partial\mu} = \frac{N_F}{1 + e^{-\mu/kT}}. \tag{4}$$

We can invert Eq. 3 to obtain μ in terms of $n = N_F E_F$ and substitute, getting:

$$\chi_0 = N_F(1 - e^{-E_F/k_B T}), \tag{5}$$

and

$$D_{c0} = \frac{\sigma_c}{e^2 N_F (1 - e^{-E_F/k_B T})}. \tag{6}$$

D_{c0}, expressed in other equivalent forms, has been used widely as an estimate for the spin diffusion coefficient expected when many-body renormalization of the spin susceptibility can be neglected. It has the familiar limits $v_F^2\tau/2$ and $v_{th}^2\tau/2$ in the degenerate and nondegenerate limits, respectively (v_F is the Fermi velocity, $v_{th} \equiv \sqrt{2k_BT/m^*}$ is the thermal velocity, and τ is the transport mean-free-time). The surprising conclusion of our measurements is that for high-electron-density, low-disorder 2DEG's, where many-body renormalization is expected to be very weak, electron-electron collisions nevertheless control D_s and reduce it well below D_{c0}.

Measurement of τ_s. For our sample with T_F = 400 K, electronic motion over lengths comparable to the spin-grating's wavelength Λ is diffusive at high temperature and ballistic at low temperature, yielding $\gamma_q = D_s q^2 + \tau_s^{-1}$ and $\gamma_q = v_F q + \tau_s^{-1}$, respectively. Though measurement of only γ_q can distinguish these two behaviors, they are more clearly distinguished when τ_s is also measured.

We measure τ_s independently of γ_q through the decay of circular dichroism (see, for instance, Refs. 3, 5). A circularly polarized pump-beam excites spatially homogenous spin polarization, which results in circular dichroism; a time-delayed probe pulse has circular polarization either the same as (SCP) or opposite to (OCP) that of the pump. The transient changes in transmitted intensity of the SCP and OCP cases are subtracted, giving the time-dependence of the spin polarization, from which we determine the decay rate, τ_s^{-1}. The results of this measurement appear in Fig. 1 (of this supplement) for the highest-electronic-density sample. The $\gamma_q - \tau_s^{-1}$ we obtain (Fig. 1, inset, of the paper) indicates that γ_q crosses over from diffusive to ballistic at low temperatures.

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Figure 1 Decay of homogenous spin excitation. Data are for the sample with T_F = 400 K. γ is the initial decay rate of the spin polarization.