Microscopic theory for the Doppler velocimetry of spin propagation in semiconductor quantum wells

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We provide a microscopic theory for the Doppler velocimetry of spin propagation in the presence of spatial inhomogeneity, driving electric field and the spin orbit coupling in the (001) GaAs quantum wells in a wide range of temperature regime based on the kinetic spin Bloch equation. It is analytically shown that when the spin-orbit coupling is weak enough and only the elastic scattering is important, the spin density wave with wave vector q envolves as

$$S_z(x,t) = S_z(q,0)\exp[-(Dq^2+1/\tau_s)t]/2 \times \left\{e^{-2Dqq_0t}\cos[qx-v_d(q+q_0')t]+e^{2Dqq_0t}\cos[qx-v_d(q-q_0')t]\right\}. \quad (1)$$

Here D, τ_s and v_d are the spin diffusion coefficient, spin relaxation time of the spin density wave and the drift velocity under the electric field E, respectively. q_0 and q_0' are determined by the spin-orbit coupling. Therefore under an applied electric field, the spin density wave gains a time-dependent phase shift $\phi(t)$. Without the spin-orbit coupling ($q_0 = q_0' = 0$), $\phi(t) = v_d q t$ which is equivalent to a normal Doppler shift in optical measurements. Without the applied electric field ($v_d = 0$) the amplitude of the spin density wave decays biexponentially with fast and slow rates $Dq^2 + 1/\tau_s \pm 2Dqq_0$. Due to the joint effect of spin-orbit coupling and the applied electric field, the phase shift behaves differently at the early and the later stages. At the early stage, the fast and slow modes share the same weights, therefore the phase shifts are the same with or without the spin-orbit coupling. While at the later stage, the phase shift becomes $\phi(t) = v_d(q - q_0)t$ and deviates from the normal Doppler one as the the slow mode becomes dominating mode. The crossover time from the early normal Doppler behavior to the anomalous one at the later stage is about $t_c \sim 1/(4D|qq_0|)$, which is inversely proportional to the spin diffusion coefficient, wave vector of the spin density wave and the spin-orbit coupling strength. In the high temperature regime, the crossover time becomes large as a result of the decreased spin diffusion coefficient. The analytical results capture all the quantitative features of the experimental results, while the full numerical calculations agree quantitatively well with the experimental data obtained from the Doppler velocimetry of spin propagation [1]. We further predict that the coherent spin precession, originally thought to be broken down at high temperature, is robust up to the room temperature for narrow quantum wells. We point out that one has to carry out the experiments longer to see the effect of the coherent spin precession at higher temperature due to the larger crossover time [2].

We also study the ambipolar transport of the spin density wave in (111) GaAs quantum well. Due to the smaller hole diffusion coefficient and enhanced hole spin relaxation time in (111) quantum well near the cancellation gate voltage [3], both hole and electron spin could be important. In some cases hole spin could even surpass the electron spin. This is quite different from the case in (001) quantum well, where hole spin quickly diminishes.

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[3] L. Wang and M. W. Wu, Phys. Rev. B **85**, 235308 (2012).