Emergence of the persistent spin helix in semiconductor quantum wells.

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Recommended with a Commentary by Bertrand I. Halperin, Harvard University.

This paper reports the first experimental observation of the "persistent spin helix", a phenomenon that has been predicted to occur, under appropriate circumstances, in a two-dimensional electron system in a GaAs quantum well. The work is a clever experimental implementation of a lovely theoretical idea. In addition, the experiments provide a new way to determine the spin-orbit coupling coefficients for the wells under study, which at least for some of the parameters, may be more accurate than any other available methods. Improved understanding and control of these parameters could have implications for the eventual construction of a spin transistor.

An electron in a GaAs quantum well, grown on a (001) surface, may be described by an effective two-dimensional Hamiltonian of the form:

$$H = \frac{\hbar^2 k^2}{2m} + (\beta - \alpha) k_x \sigma_y + (\beta + \alpha) k_y \sigma_x + \frac{\gamma}{2}(k_y^2 - k_x^2)(k_x \sigma_y - k_y \sigma_x)\,.$$

Here, k is the magnitude of the wave vector in the x-y plane, and α, β, γ are spin-orbit coupling constants. We have assumed that the electron is confined to the lowest sub-band in the z-direction. The x and y axes are here chosen to lie in the (110) and $(1\bar{1}0)$ directions, rotated by 45 degrees relative to the convention used in the paper. The Rashba coupling constant α depends on the asymmetry of the well, and should vanish in the case of a symmetric well. The linear Dresselhaus coupling constant β exists even for a symmetric well, and is most sensitive to the thickness of the well. The cubic Dresselhaus coupling constant γ is, in principle, a characteristic of bulk GaAs, but its value may be modified by the AlGaAs barriers at the sides of the well.

In the special case where $\alpha = \beta$, if the γ term is neglected, the Hamiltonian has a special symmetry. The remaining spin orbit coupling can be removed entirely if one makes a unitary transformation U in which the axis of spin quantization depends on the position of the electron. Specifically, U should be chosen to rotate the spin direction about the x-axis by an angle $\theta(y) = Qy + \text{constant}$, where $Q = 4m\alpha\hbar^{-2}$. Since U commutes with the Coulomb interaction between electrons, the transformed Hamiltonian H' will commute with the total transformed spin $\vec{S}'$, even when interactions are important, so that $\vec{S}'$ will be a true constant of the motion.[1] Of course, when the cubic coupling term is taken into account, spin decay will occur, but there still can be a dramatic reduction in relaxation when the parameters α and β are tuned to be equal. (Similar effects will occur if $\alpha = -\beta$, but the x and y axes will be interchanged.)

As has been noted in the past by various authors[2], under the conditions $\alpha = \beta$ and $\gamma = 0$, the effect of spin-orbit coupling on charge transport should be eliminated (e.g., the orbital magnetoconductance is similar to that of a system without spin-orbit coupling, with no weak antilocalization effect in zero magnetic field). The usual Dyakanov-Perel mechanism for spin relaxation is suppressed; an electron inserted at a point $\vec{r}$ with spin in a given direction $\hat{n}$ will have its spin in the same direction, if it is detected at the same point at a later time, after diffusing around an arbitrary path. The predicted absence of weak anti-localization is a consequence of the fact that the spin and charge propagators for an electron to return to the origin are found to be identical to those of a system without spin-orbit coupling. If the electron is detected at a point $\vec{r}' \neq \vec{r}$, its direction will be rotated about the x-axis by a definite angle, $\theta(y') - \theta(y)$. Schliemann, Egues, and Loss[3] remarked on this rotation of spin direction, and proposed to use the absence of relaxation to produce a spin transistor in the non-ballistic regime.

Three years ago, Bernevig, Orenstein, and Zhang[1] pointed out that one could use a pulsed laser to produce a helical spin structure with a chosen wavevector and to monitor its decay. If the spin-orbit coupling constants are adjusted to the condition $\alpha = \beta$, and the wavevector of the induced spin helix is properly chosen, then the structure can be exceptionally long lived, which Bernevig et al. termed a "persistent spin helix." The present work realizes that proposal.

Experiments were carried out using samples with ten quantum wells, separated by AlGaAs barriers. A non-zero asymmetry-parameter α was achieved by using alternating concentration of Si donors in the barriers between successive layers; the value of α was changed by varying the magnitude of the difference in concentrations. The parameter β was changed by varying the thickness of the wells. Transient spin polarization waves, with a sinusoidal modulation at a controlled wavevector q_x in the x-direction, were produced using optical interference of two cross-polarized pulses from a single pulsed laser. Time-evolution of the spin polarization was measured with a timedelayed probe pulse, which was diffracted by the spin grating due to the Kerr effect. As the initial grating is linearly polarized in the z-direction, it can be a considered a superposition of two helical waves with polarization in the x-z plane and wavevectors $\pm q_y$, which have separate time evolutions. In the case where $\gamma = 0$ and $\alpha = \beta$, the two components should relax exponentially at rates $\eta_\pm = D_s(q_y \pm Q)^2$, where $Q = 4m\alpha\hbar^{-2}$ as above, and D_s is the spin diffusion rate for the electrons that would occur in the absence of spin-orbit coupling. The relaxation rates are more complicated for the general situation, where $\alpha \neq \beta$ and $\gamma \neq 0$, but a theory has been worked out by Stanescu and Galitski.[4] Koralek et al. find that their data is well fit by this theory, and this enables them to extract the parameters α, β, γ, and D_s.

Of particular interest is the value of the bulk parameter γ, which should be relatively insensitive to details of the well, but whose quoted value has varied widely in past estimates. The value obtained here is $\gamma \approx 5$ eV Å^2, which is on the low end of previous estimates and first-principles calculations.[5] The authors' estimate of γ come both from the direct value obtained from their fits and from the fitted values of β, using the predicted (approximate) relation between γ and β expected for a quantum well of known thickness d.

The temperature-dependence of the spin-helix relaxation is also quite interesting. Some of this dependence can be understood as arising from temperature-dependence of the spin diffusion constant D_s, which decreases strongly with increasing temperature due to the effects of electron-electron scattering ("spin Coulomb drag"). But other features remain to be explained.

References.

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