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1999 J. Phys.: Condens. Matter 11 L407

(http://iopscience.iop.org/0953-8984/11/37/101)

J. Phys.: Condens. Matter **11** (1999) L407–L414. Printed in the UK PII: S0953-8984(99)04081-3

LETTER TO THE EDITOR

Nuclear spin-orientation dependence of magnetoconductance: a new method for measuring the spin of charged excitations in the quantum Hall effect

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Received 7 May 1999, in final form 16 August 1999

Abstract. A new method for measuring the spin of the electrically charged ground-state excitations in the quantum Hall effect is proposed and demonstrated for the first time for GaAs/AlGaAs multiquantum wells. The method is based on the nuclear spin-orientation dependence of the two-dimensional direct-current conductivity in the quantum Hall regime due to the nuclear hyperfine interaction. We use this method to determine the spin of the electrically charged excitations of the ground state at filling factor $\nu = 1$.

Recently the quantum Hall effect (QHE) at Landau level (LL) filling factor $\nu = 1$ has aroused much interest. Theory [1] has predicted ferromagnetic order in the 2D electron system (2DES) in AlGaAs/GaAs quantum well (QW) structures and therefore nontrivial topological defects (Skyrmions) of the ground state. A variety of experimental techniques have provided evidence for the existence of these spin-texture excitations, including NMR [2], thermally activated transport [3], and electron–hole recombination luminescence polarization [4]. According to theory, the relevant parameter governing the number of spin flips s associated with the excitation is the dimensionless Zeeman energy $\tilde{g} \equiv |g|\mu_B B_0/(e^2/\epsilon l_0)$, where $g \approx -0.4$ is the single-electron Landé g-factor, $l_0 = (\hbar/eB_\perp)^{1/2}$ is the magnetic length, ϵ is the dielectric constant of GaAs, and $B_\perp$ is the component of the total magnetic field B_0 normal to the 2DES. Hartree–Fock calculations incorporating LL mixing and finite-thickness effects [5] indicate that $s > 1$ when $\tilde{g} \leqslant 0.025$. However, the agreement between these calculations and the experimental data is not yet exact, and there are inconsistencies between different experimental reports [2–4] of the spin polarization around $\nu = 1$. Another unresolved problem is the disagreement (by a factor of 2) between the theoretically and experimentally determined values of the energy gap between the ground state and the excitations [6].

Here we present a new method for determining s based on the effect of local nuclear hyperfine fields on the 2D dc conductivity, σ_{xx}. We experimentally demonstrate this method at $\nu = 1$, but it should also be suitable for measuring spin-energy gaps pertaining to fractional fillings. There are several key advantages of this new method in comparison to existing methods [2, 3]. Firstly, B_0 and $B_\perp$ are nominally held constant, thereby circumventing LL mixing and subband energy changes that can potentially occur when $B_\perp$ or B_0 are varied [5].

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0953-8984/99/370407+08$30.00

Secondly, measurements are carried out at constant temperature T. Thus, any T-dependence of the exchange energy Δ_0 does not effect the g-factor determination. In the tilted-field experiments [3], quantitative results can be obtained only at a very low T where Δ_0 is presumed to be T-independent. Our method circumvents these limitations and provides, in principle, a unique way to measure the T-dependence of the exchange-enhanced g-factor when $s > 1$. In this letter, we will demonstrate how s can be measured at a single, fixed T.

As in previous thermal activation energy gap determinations for the lowest LL [3, 7], our analysis is based on the assumption that at thermal equilibrium the gap can be separated into two terms,

$$E^{\mathrm{eq}} = \Delta_0 + s|g|\mu_B(B_0 + B_n^{\mathrm{eq}}) \tag{1}$$

where Δ_0 is the exchange energy ($\sim e^2/\epsilon l_0$) due to e–e interaction and $s|g|\mu_B B_0$ is the Zeeman energy term. Following reference [12], we have also included the Zeeman term derived from the nuclear hyperfine contact interaction averaged over all nuclei in the vicinity of the 2DES, $B_n^{\mathrm{eq}} = A\langle I_z\rangle^{\mathrm{eq}}$, where A is the hyperfine coupling constant and $\langle I_z\rangle^{\mathrm{eq}}$ is the nuclear spin polarization. In the absence of spin–orbit interaction, as in the conduction band of GaAs [7, 8], the electron–nuclear hyperfine contact interaction acts on the electron spin state exclusively. Normally, this nuclear spin term can be neglected, but, as in reference [12], we will describe experiments in which it is significantly enhanced. The factor s accounts for the possible occurrence of spin-texture excitations (i.e. Skyrmions) in the 2DES. It is shown in reference [3] that s can be determined from the rate of change of the energy gap as a function of B_0 at constant $B_\perp$. As a direct extension we have introduced s into the expression for the nuclear hyperfine contribution to the Zeeman energy of the electron. This is a generalization of the spin–spin Fermi contact interaction, $\hat{\mathcal{H}} = A' \sum_i \hat{S} \cdot \hat{I}_i$, where the magnetic moment of a single electron, $g\mu\hat{S}$, is replaced by the magnetic moment of the magnetic excitation, $sg\mu\hat{S}$. The assumed space uniformity of the nuclear polarization allows the summation to be replaced by the average expectation value: $\sum_i \hat{I}_i \to \langle\hat{I}_z\rangle$. Note that an equivalent Hamiltonian was previously used [2] to describe NMR Knight shifts in the presence of Skyrmions at $\nu = 1$.

Under our experimental conditions, where $T \approx 2.5$ K and $B_0 = 5.35$ T, the longitudinal conductivity at $\nu = 1$ obeys an Arrhenius law:

$$\sigma_{xx}^{\mathrm{eq}} = \sigma_0 \exp(-E^{\mathrm{eq}}/2kT) \tag{2}$$

where σ_0 is a constant, assumed to be independent of B_n, and E^{eq} is the energy of ground-state excitations. Consider the effect on σ_{xx} if the nuclear polarization is enhanced by a method such as dynamic nuclear polarization (DNP) [9–12]. Recall that in DNP, the nuclear spin polarization becomes enhanced by cross-relaxation with electron spin levels driven toward saturation by electron spin resonance. Combining equation (1) and equation (2),

$$\Delta\sigma_{xx}/\sigma_{xx}^{\mathrm{eq}} = -s|g|\mu_B\,\Delta B_n/2kT \tag{3}$$

where $\Delta\sigma_{xx} = \sigma_{xx}^{DNP} - \sigma_{xx}^{eq}$, $\Delta B_n = B_n^{\mathrm{DNP}} - B_n^{\mathrm{eq}}$, and B_n^{DNP} is the DNP-enhanced local nuclear field. In writing equation (3), the use of the high-temperature approximation $|g|\mu_B\,\Delta B_n \ll 2kT$ is justified, since ΔB_n will be limited to $\leqslant 200$ mT in our experiments. We see that the relative variation of the longitudinal conductivity is proportional to the number of spin flips s in the excitation. Therefore, s can be extracted from the slope of a plot of $\Delta\sigma_{xx}/\sigma_{xx}^{\mathrm{eq}}$ versus $-|g|\mu_B\,\Delta B_n/2kT$. It is evident that any T-dependence of Δ_0 is irrelevant since this factor plays no role in equation (3). In principle, spin-exchange scattering due to the hyperfine interaction is yet another mechanism by which the conductivity can be affected by the degree of nuclear spin polarization, where, according to theory [13], $\sigma_{xx} \propto \langle I_z\rangle^2/T^2$. However, a simple estimation [13] indicates that the dependence of the conductivity on the nuclear spin polarization due to spin-exchange scattering is very weak at temperatures of the order of a few K. Furthermore, equation (3) predicts a linear dependence of $\Delta\sigma_{xx}/\sigma_{xx}^{\mathrm{eq}}$ versus $-|g|\mu_B\,\Delta B_n/2kT$ with a slope s. The experimental data that we present below exhibit a linear dependence, with a slope s close to unity. This result is consistent with the assumption that the dependence of the longitudinal conductivity on the nuclear field is dominated by the activated transport law given in equation (2).

To measure σ_{xx} for the AlGaAs/GaAs multi-QW samples we have employed a standard four-probe method at temperatures in the 1.7–4.2 K range. To enhance the nuclear spin polarization, a down-field-swept microwave DNP technique was employed [12]. The Overhauser shift of the electron spin-resonance (ESR) line served as a detector of ΔB_n. The ESR was detected electrically as described in references [14] and [15]. Although the mechanism for this phenomenon is not yet fully understood, it nevertheless provides a working method for detecting and controlling the nuclear hyperfine contribution to the Zeeman energy [12, 15].

The AlGaAs/GaAs multi-QW samples were grown by molecular beam epitaxy. At $T = 4.2$ K sample EA124 (21 GaAs wells, 300 Å well widths, $Al_{0.1}Ga_{0.9}As$) has a 2D electron density per layer of $n_S = 6.9 \times 10^{10}$ cm^{-2} and mobility $\mu = 440\,000$ V cm^{-2} s^{-1}. For the second sample, EA216 (40 GaAs wells, $Al_{0.3}Ga_{0.7}As$ barriers), $n_S = 1.2 \times 10^{11}$ cm^{-2} and $\mu = 650\,000$ V cm^{-2} s^{-1}. The samples were mounted on a rotation stage to allow the $\nu = 1$ filling factor to be obtained at the desired electron spin-resonance/magnetic field condition. ρ_{xx} was measured at 524 Hz using a lock-in amplifier. To increase the sensitivity for ESR detection, the microwave power was modulated at a frequency of 7 Hz. The output of this first amplifier was connected to the input of a second lock-in amplifier which detected $\Delta\rho_{xx}$ induced by the microwave excitation at 7 Hz. This method helps to avoid the rectification signal at 7 Hz induced by the microwave electromagnetic field.

Figure 1 shows ρ_{xx} and ρ_{xy} for sample EA124 at $T = 0.3$ K in the $B_0 = B_\perp$ orientation. The inset shows a typical electrically detected ESR spectrum recorded at $T = 1.7$ K by a field up-sweep using a fixed frequency of 32.48 GHz. In the procedure for polarizing the nuclear spins by DNP in a 2DES [12], the microwave generator is switched to continuous-wave mode

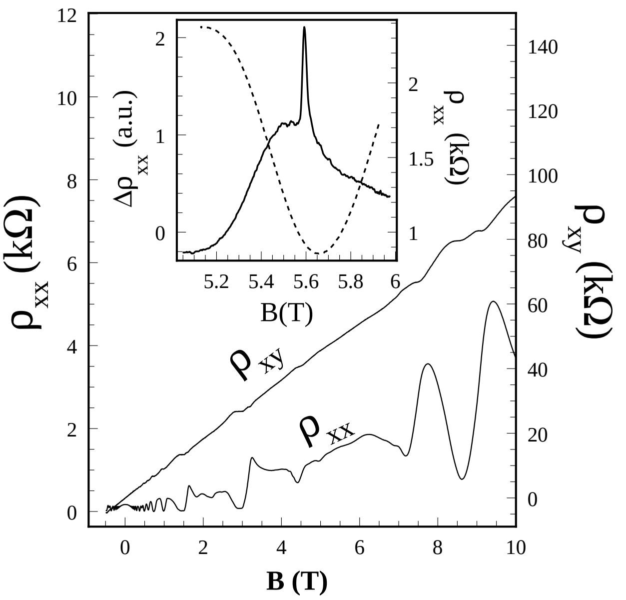

Figure 1. QHE traces (ρ_{xx} and ρ_{xy}, per layer, per square) for EA124 at $T = 0.3$ K, $\theta = 0$, with $\nu = 1$ at $B_0 = 2.9$ T. Inset: the field dependence of ρ_{xx} per layer (dashed curve) and the change due to the microwave excitation at 32.48 GHz near $\nu = 1$ at $T = 1.7$ K, $\theta = 60^\circ$. From the ESR, $g = -0.415$.

with no amplitude modulation. The external field B_0 is initially set to a value slightly higher than $B_n^{\rm eq}$, the field corresponding to the ESR condition with the nuclear spins at thermal equilibrium. The dynamic polarization of the nuclear spins is induced by a slow down-field sweep of B_0. As a result of saturation of the ESR transition and electron–nuclear cross-relaxation, an enhancement of the nuclear spin polarization is induced. As the nuclear field increases it provides an additional internal field B_n through the hyperfine interaction which produces an Overhauser shift of the ESR line. In GaAs this shift is to higher B_0 because $g < 0$ [11]. By choosing an appropriate down-sweep rate while keeping the microwave frequency constant, it is possible to shift the ESR line considerably [12]. With our experimental set-up, a maximum Overhauser shift $B_n^{\rm eq} - B_n^{\rm DNP} = 0.2$ T was achieved at $B_0 = 5.5$ T.

In accordance with equation (3) the enhancement of B_n should change σ_{xx} under QHE conditions. This is demonstrated in figure 2. which presents the B_0-dependence of σ_{xx} at $T = 2.5$ K for sample EA124. To ensure that the nuclei were initially at thermal equilibrium, the 2D electron system was adjusted slightly away from the ρ_{xx}-minimum at $\nu = 1$ for 300–600 s before the first sweep. This equilibration delay is much longer than the anticipated nuclear spin-relaxation time under these conditions [2, 15]. To observe the small difference in the dc conductivity we first made an up-sweep of B_0 without microwave excitation with the nuclei in thermal equilibrium with the lattice. After recording the control trace for ρ_{xx}

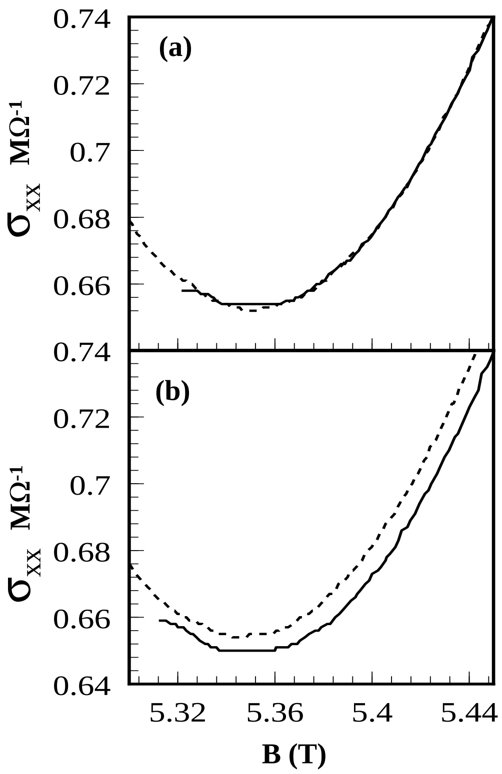

Figure 2. EA124 field dependences of σ_{xx} (per layer) before (dashed curves) and immediately following (solid curves) microwave excitation during the down-sweep of B_0 at $T = 2.50$ K near $\nu = 1$. In (b), the nuclear spin polarization was enhanced by DNP. The frequency 32 GHz corresponds to ESR at $B_0 = 5.5$ T before DNP. In (a), the same microwave power was applied but at 20.0 GHz, a frequency outside the ESR range, so that the nuclear polarization is not enhanced.

with the nuclear spin polarization at thermal equilibrium, the nuclei were then polarized by the down-swept DNP method described above. We employed a rate of down-sweep of B_0 of $dB_0/dt \approx 0.5$ mT s^{-1} near $\nu = 1$ for a duration of 180–300 s. To subsequently measure the Overhauser shift, the ESR spectrum was recorded in a second up-sweep of B_0 while the nuclei were still polarized. We observed that the Overhauser shift relaxation time at $\nu = 1$ and $T = 2.7$ K is about 240–300 s. Since this is much longer than the timescale of the detection up-sweep (about 30 s), the amount of nuclear spin relaxation during the detection scan is relatively small and may be neglected.

To be sure that the observed conductivity changes are associated with DNP-enhanced nuclear spin polarization and do not have some other origin such as a persistent microwave conductivity effect, we also measured $\Delta\sigma_{xx}$ using exactly the same multiple-up-sweep detection procedure as described above but with a microwave irradiation well away from resonance from the ESR condition. This did not shift the ESR line position and did not appreciably change σ_{xx} for sample EA124.

The time evolution of $\Delta\sigma_{xx}(t)$ near $\nu = 1$ in EA-124 is demonstrated in figure 3(a). Here, the nuclear spin polarization was enhanced by DNP with a down-sweep of B_0 that terminated at 5.34 T (where $\nu = 1$ is at 5.35 T). Following termination of the sweep, the microwaves were switched off, and the decay in σ_{xx} recorded as a function of time. Figure 3(b) shows the time dependence of the Overhauser shift following DNP in sample EA124 over a 100 mT region close to $\nu = 1$. The relaxation times determined from simple exponential fits to the dc conductivity and Overhauser shift decays are very similar. The slight discrepancy between the

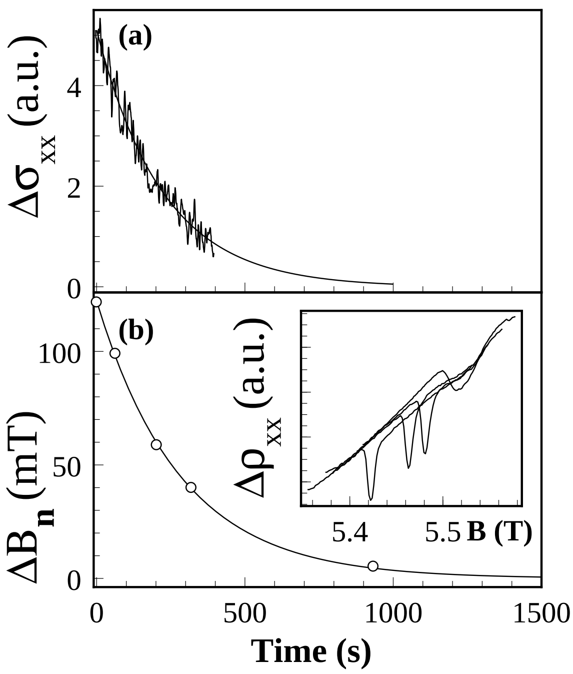

Figure 3. (a) Time evolution of $\Delta\sigma_{xx}$, at $B_0 = 5.34$ T and $T = 2.51$ K, immediately after DNP in EA124. $T_{1n} = 230$ s was found from an exponential fit. (b) The dependence of ΔB_n determined from repeated Overhauser shift measurements at $T = 2.7$ K, 32.2 GHz. Inset: the B_0-dependence of the electrically detected ESR at different times following DNP. $T_{1n} = 279$ s was found from an exponential fit, as shown.

values is probably associated with the difference between the actual filling factors obtained in each of the experiments. The small additional nuclear polarization induced by the brief exposure to an on-resonance microwave field during the Overhauser shift measurements may also contribute to the error.

Finally, we report the simultaneous measurement of $\Delta\sigma_{xx}$ and ΔB_n in EA124 which allows s to be determined on the basis of equation (3). In this procedure, the nuclear spins are initially at thermal equilibrium, and the ESR field corresponds to $B_n^{\rm eq}$. The nuclear spins are then polarized by applying the microwaves while slowly ramping down the external magnetic field to a series of different terminating fields $B_n^{\rm DNP}$. Although the ESR spectrum and hence the Overhauser shift are not actually observed in this experimental procedure, we are nevertheless certain that the desired local nuclear field, ΔB_n, has been induced by the down-field-swept DNP procedure because the DNP conditions, including the initial applied magnetic field, frequency of the polarizing microwaves, and magnetic field down-sweep rate, have already been established in a prior experiment in which the ESR was detected immediately following the switching off of the microwaves at varying terminating fields. These conditions were found to consistently produce the desired local nuclear field. At each value of $B_n^{\rm DNP}$, the microwaves are switched off and σ_{xx} recorded. At the moment at which the microwaves are switched off, the change in the nuclear field which maintains the ESR condition is given by $\Delta B_n = B_n^{\rm DNP} - B_n^{\rm eq}$, i.e. the Overhauser shift. Thus, ΔB_n and $\Delta\sigma_{xx}$ are obtained simultaneously.

In figure 4 we have plotted $\Delta\sigma_{xx}/\sigma_{xx}^{\rm eq}$ against $|g|\mu_B\,\Delta B_n/2kT$ for different values of $\Delta B_n^{\rm DNP}$. The dc conductivity difference $\Delta\sigma_{xx}$ was measured as the difference between minima of the $\sigma_{xx}(B)$ trace before and immediately after DNP enhancement, as in figure 2. The inset shows an Arrhenius plot of the longitudinal resitance, ρ_{xx}. Least-squares fitting over the low-temperature range of the data yields an energy gap of 8.1 K. This gap is smaller (by a factor of

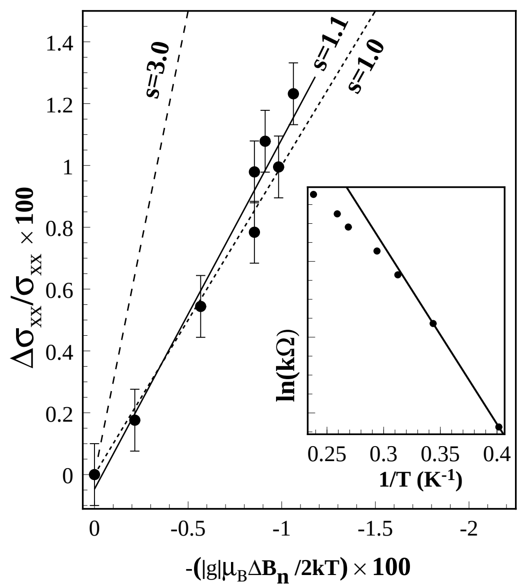

Figure 4. The dependence of $\Delta\sigma_{xx}/\sigma_{xx}$ on the factor $|g|\mu_B\,\Delta B_n/2kT$ for different values of the DNP-enhanced Overhauser shift, ΔB_n. The slope $s = 1.1 \pm 0.15$, determined from the best linear fit as indicated by the solid line, corresponds to the number of spin flips involved in the excitations within the LL. The data are for EA124 at $T = 2.50$ K, $F = 32$ GHz. Inset: the T-dependence of ρ_{xx}, in kΩ/(layer square).

2–3) than the $\nu = 1$ gaps reported in reference [3]. This is probably due to several contributing factors. First, sample EA-124 is a multi-QW structure, rather than a single heterointerface as in reference [3]. In multi-QW samples, well-to-well variations in the electron density and filling factor can occur at a single value of the applied magnetic field. This heterogeneous distribution results in a reduction of the apparent activation energy. Second, EA-124's comparatively lower zero-field mobility will also contribute to a reduced apparent activation energy [3]. These factors will to an unknown extent limit the ability to extract a quantitative and well defined value of s. Nevertheless, the fact that the experimental data yield a reasonable value of $s \approx 1$ which is roughly what is expected from equation (3) strongly supports the validity of the experimental data and its analysis. Equivalent experiments performed on the second sample, EA216, produced similar results.

In the absence of spin–orbit coupling, as in the conduction band of GaAs, the e–e interaction does not change the ESR frequency in the spatially uniform (infinite-skin-depth) case [16]. This is because the spin Hamiltonian representing the interaction of the electron spin with the static and transverse microwave magnetic fields commutes with the orbital Hamiltonian, including e–e interactions. Although the microwave field is not highly uniform in the quantum wells due to screening, this can be neglected, considering that the space scale of the e–e interaction is of the order of the magnetic length ($\approx$15 nm), while the screening of the electromagnetic field occurs on a larger scale of about 1 μm. Thus, it is valid to consider the ESR as a pure one-electron phenomenon with the Larmor frequency determined by the observed bare g-factor, $g = -0.41$.

In fulfilment of equation (3), the data in figure 4 obey a linear dependence on ΔB_n. The slope yields $s = 1.1 \pm 0.15$ spin flips per excitation, as determined by linear least-squares fitting. Thus, the Zeeman term in the excitation energy at $\nu = 1$ and $B_0 = 5$–6 T and $T = 2.5$ K corresponds to about one electron spin flip per one ground-state electrically charged excitation.

In conclusion, the effect of the nuclear spin polarization on the dc conductivity of 2D electrons under QHE conditions at $\nu = 1$ was observed in AlGaAs/GaAs multiquantum wells. The relaxation decay time of the dc conductivity is close to the value for the relaxation of the nuclear spin polarization. The variation of the 2D electron dc conductivity is proportional to the nuclear spin polarization measured via the Overhauser shift of the electrically detected 2D ESR at filling factor $\nu = 1$. The observed effect is consistent with the assumption that the ground-state excitation energy at $\nu = 1$ can be regarded as a sum of the Zeeman and exchange energy terms. For sample EA124, where $\tilde{g} = 0.017$ at $B_0 = 5.3$ T, the Zeeman energy corresponds to $s = 1.1 \pm 0.2$ spin flips per excitation. Our future work will entail repeating the experiments described herein with higher-mobility single-QW structures at lower temperatures to obtain higher accuracy in the determination of s at various $\tilde{g}$-values.

Technical assistance at NHMFL was received from M Whitton, B Pullum, and B Brandt. This work was supported by NSF grant CHE-9624243 and US DOE contract DE-AC04-94AL85000. The NHMFL is supported by NSF Cooperative Agreement No DMR-9527035 and by the State of Florida.

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