Spin Excitations of a Two-Dimensional Electron Gas in the Limit of Vanishing Landé g Factor

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Electrical transport measurements under hydrostatic pressure have been used to determine the enhanced spin gap at filling factor $\nu = 1$ in the limit of vanishing Landé g factor ($|g| \leq 0.1$). The enhanced spin gap exists even when $g = 0$, and the observed variation of the spin gap around $g = 0$ is qualitatively consistent with recent predictions that the lowest charged excitation has a nontrivial spin order (Skyrmion). [S0031-9007(96)01734-6]

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Until recently it was accepted that the energy spectrum of a two-dimensional electron gas (2DEG) at a Landau level filling factor $\nu = 1$ consists of a single particle ground state and the excitation spectrum of spin waves [1,2] with dispersion relations $E(\vec{k}) = g\mu_B B + (\sqrt{\pi/2}\, e^2/\epsilon l_B)[1 - e^{-k^2 l_B^2/4} I_0(k^2 l_B^2/4)]$, where $\vec{k}$ is the corresponding wave vector, g is the effective single particle Landé g factor and $l_B = \sqrt{\hbar/eB}$ is the magnetic length. This is only in qualitative agreement with experiments: The thermally activated gaps measured with transport techniques (which are sensitive to charged, long wave-vector excitations) have been reported [3,4] to be significantly enhanced compared to "optical gaps" [5] determined by neutral, short wave-vector excitations equal to the single particle energy splitting $g\mu_B B$ [6]. Recent theoretical papers [7,8] propose that, at $\nu = 1$, the interplay between Zeeman and Coulomb interaction leads to a more complex excitation spectrum which involves "Skyrmion-type" charged excitations with unusual spin order [9,10]. The experimentally observed [11,12] sharp spin depolarization of a 2DEG on both sides of $\nu = 1$ has been assigned to an unusual spin order of the ground state for filling factors slightly different from unity [13]. The essential parameter in the theory is the ratio $g^* = g\mu_B B/(e^2/\epsilon l_B)$, i.e., the ratio of the Zeeman and Coulomb energies involved in the problem. The most interesting effects are expected in the range of $g^* \sim 0$, where the energy of Skyrmion-type excitations is expected to change rapidly as a function of the effective g factor. This energy is exactly equal to half of the energy of the long wave-vector spin-wave excitation at $g^* = 0$, whereas, for larger g^*, the lowest Skyrmion-type excitations are of a finite size, and, already at $g^* \sim 0.01$, become almost identical with long wave vector spin-wave excitations [7,8,14]. Experimentally, g^* can be tuned by tilting the magnetic field [15], although such experiments are usually limited to the range of weak Coulomb interaction where Landau level mixing can appreciably modify the respective energetic position of the Skyrmion and the usual spin-wave excitations [16].

In this Letter we report on activated magnetotransport studies of the excitation spectrum of a 2DEG at filling factor 1 and its dependence on the effective g factor which is tuned in the range between -0.11 to $+0.065$ by applying the hydrostatic pressure to the investigated 6.8 nm thick GaAs/GaAlAs modulation doped quantum well. The technique used allows us to investigate the region where $|g^*| < 0.01$, which is particularly interesting in view of the Skyrmion model. The limit of a relatively strong Coulomb interaction is probed since in our experiments the filling factor 1 is obtained at $B = 11.6$ T. The experimentally determined spin activation gap E_A remains open for all values of g, including the $g = 0$ limit. The measured values of E_A are, however, lower than theoretically expected which is tentatively assigned to the effect of disorder. The g-factor dependence of spin activation energy is significantly enhanced as compared to the $g\mu_B B$ dependence predicted by the spin-wave approach. The Skyrmion model explains well the data, and the appearance of large size spin-texture excitations is concluded in the limit of the vanishing g factor.

Hydrostatic pressure has been used previously to probe the spin polarization of fractional states in GaAs/GaAlAs heterostructures [17]. The effective electronic g factor in a semiconductor is determined mostly by spin-orbit coupling [18,19] and therefore changes, for example, with either the application of hydrostatic pressure or with quantum confinement. It has been estimated [20,21] that in the case of GaAs-based structures under normal conditions the bare g factor is zero for a quantum well width $\simeq$5.5 nm. We have investigated a slightly wider quantum well with a negative and relatively small g factor which will increase and pass through zero with the application of hydrostatic pressure. For the investigated

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structure, we find that the bare g factor is zero for an applied pressure of 4.8 kbars, and we have calculated the variation of the g factor around zero using a 5-band $\vec{k} \cdot \vec{p}$ model [19]. In the pressure range, 0–8 kbars, the g factor varies almost linearly between -0.11 and $+0.065$.

For the investigation a 6.8 nm modulation doped GaAs/AlGaAs quantum well was grown by molecular beam epitaxy. A Hall bar was defined using standard photolithographic and etching techniques. The low temperature (4.2 K) mobility is (100 000–400 000) $\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$ and the sheet carrier concentration $(1\text{–}3) \times 10^{11}\ \text{cm}^{-2}$ depending upon the prior illumination. For the measurements the sample was mounted in a liquid clamp pressure cell. The pressure is applied at room temperature, and the cell is then cooled to low temperature for the measurement. Cooling is accompanied by a slight reduction in pressure. Over the temperature range of interest ($T < 10$ K), the change in pressure is negligible. All pressures were measured at low temperature by means of a calibrated InSb gauge. The sample could be illuminated *in situ* using a GaAs light emitting diode mounted inside the cell. With increasing hydrostatic pressure the dark carrier concentration decreases probably due to electron trapping at *DX* centers. The carrier concentration could be persistently increased by illuminating the sample at low temperatures. The temperature was measured using a calibrated Allen-Bradley resistor mounted outside the cell and corrected for magnetic field dependence. The temperature dependence of the magnetoresistance has been measured at a number of different pressures between 0 and 7.55 kbars. All measurements as a function of pressure were performed with a constant carrier concentration of $(2.8 \pm 0.15) \times 10^{11}\ \text{cm}^{-2}$ which was obtained after careful illumination with pulses of light. This corresponds to a filling factor of $\nu = 1$ at 11.6 Tesla. Under these experimental conditions, the low field mobility does not depend on the applied pressure and is $\simeq 200\,000\ \text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$. In Fig. 1, data for two representative pressures (4.85 and 7.55 kbars) are shown. At 4.85 kbars the bare g factor is close to zero. For a given temperature the minimum in resistance at $\nu = 1$ is strongly developed at 7.55 kbars but significantly weaker in the 4.85 kbars data. Although visible, the minima at higher odd filling factors ($\nu = 3$) are much less pronounced, preventing a reliable data analysis.

The activation energy at each pressure has been determined by means of an Arrhenius plot. It should be noted that the sample investigated has a component of ρ_{xy} mixed in with ρ_{xx} which dominates at low temperatures, preventing well developed zeros in the resistance. This can, to some extent, be corrected by subtracting twice the low temperature saturated value of ρ_{xx} at filling factor $\nu = 2$ (i.e., $560 \pm 60\ \Omega$) from $\rho_{xx}(\nu = 1)$, a procedure which works well for temperatures above 2 K. Below $\simeq 2$ K, when ρ_{xx} is sufficiently small ($\simeq 600\ \Omega$), numerical errors make this analysis unreliable. The original data (open symbols) together with the corrected resistance (closed symbols) are

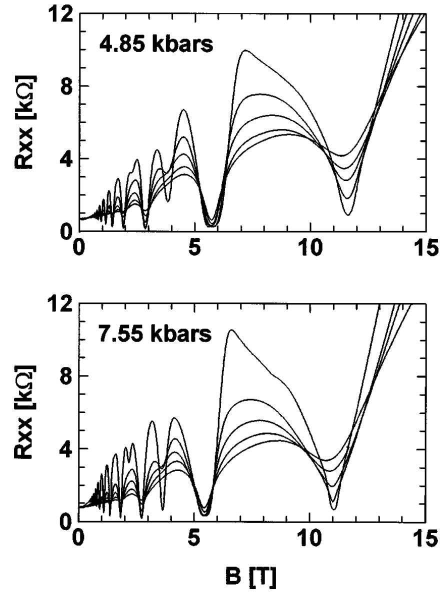

FIG. 1. Temperature dependence (2, 4, 6, 8, 10 K) of the longitudinal magnetoresistance measured at 4.85 and 7.55 kbars corresponding to a bare g factor $g \simeq 0$ and $+0.055$, respectively.

shown in Fig. 2 for two representative pressures. The corrected resistance shows a well defined activated behavior over more than 1 order of magnitude. Less than optimum sample quality is the price we pay when working with a quantum well with one low mobility interface and not with a simple heterojunction for which similar experiments would be difficult to perform, implying, for example, the working conditions beyond the limit of standard liquid clamp pressure cells (for bulk GaAs the g factor passes through zero around 17 kbars). It is apparent from the raw data that the pressure has a significant effect on the enhanced spin gap, and the change in slope of the corrected Arrhenius plots allows a reliable determination of the gap. We have fitted the corrected temperature dependence at $\nu = 1$ using the formula $\rho = \rho_0 \exp(-E_A/2kT)$, where E_A is the spin activation gap.

Figure 3 presents our main experimental finding, i.e., the dependence of the spin activation gap on the effective g factor, the latter assigned to each value of the applied hydrostatic pressure through a 5-band $\vec{k} \cdot \vec{p}$ model. The error bars reflect the error associated with subtracting the background, as described above, rather than the error in the least squares fit to the Arrhenius plots. As can be seen in this figure, the absolute values of the obtained gaps are significantly lower than predicted by the spin-wave approach ($\Delta \geq E_B = \sqrt{\pi/2}\, e^2/\epsilon l_B \simeq 213$ K at $B = 11.6$ T) as well as by the Skyrmion model ($\Delta \approx E_B/2$). In spite of this well known discrepancy [3,4,15], our result show an interesting feature, i.e., the spin activation gap changes rapidly in the region of zero effective g factor. This dependence is much stronger than predicted by the spin-wave approach $[E_s(g) = g\mu_B B + E_B]$, but can be qualitatively accounted for by using

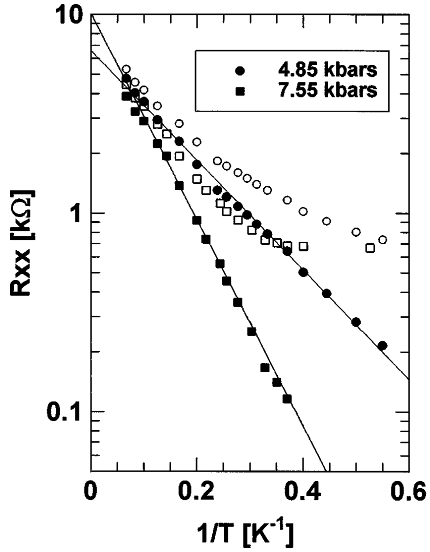

FIG. 2. Arrhenius plot of resistance at $\nu = 1$ versus inverse temperature for representative pressures. Open symbols represent the raw data; closed symbols indicate the resistance after the subtraction of the background as described in the text. The solid lines indicate least squares fit to the corrected data which are used to deduce the activation energy.

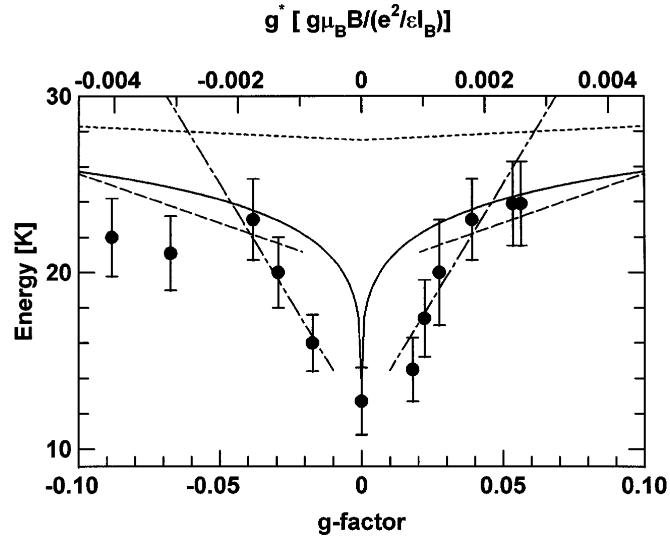

FIG. 3. The measured energy gap at filling factor $\nu = 1$ as a function of the bare g factor (bottom axis) and as a function of g^*, the ratio of the Zeeman and Coulomb energies (top axis). The solid line is the expected gap for a Skyrmion-type excitation [7], while the short-dashed line indicates the expected variation for the "bare" Zeeman dependence $E_B + s|g|\mu_B B$ (with $s = 1$ as predicted by the spin-wave dispersion model). Lines with slopes corresponding to $s = 7$ spin flips (long-dashed line) and $s = 33$ spin flips (long-short-dashed line) are shown for comparison.

the Skyrmion model which indeed implies a significant suppression of the spin-excitation gap when $g \rightarrow 0$ [7]:

$$\Delta(g) = \frac{1}{2} E_B[1 + \alpha|g \ln(g)|^{1/3}], \quad (1)$$

or

$$\Delta(g) = \frac{1}{2} E_B\left(1 + \frac{2.2}{d}\right), \quad (2)$$

where $\alpha = \frac{3\pi}{4}(\frac{18}{\pi})^{1/6}(\frac{\epsilon a_B}{\ell_B})^{1/3}$, a_B is the Bohr radius, and $d = \lambda/l_B$ is the characteristic length of the Skyrmion extension in units of the magnetic length.

For the sake of a more quantitative analysis we are forced to consider the Coulomb energy E_B as the adjustable parameter. The difference in the amplitude between measured and theoretically expected values of spin activation gaps is tentatively assigned to the effect of disorder which may be expected to weaken the pure Coulomb correlation at long distances. The solid line in Fig. 3 shows the dependence given by Eq. (1), where E_B has been set to $E_B = 27.5$ K. The experimental trends are fairly well reproduced even though the agreement is not perfect. The measured gap at $g \simeq 0$ is reduced by approximately 50% when compared with the $g \simeq 0.1$, in good agreement with the 50% reduction expected from theory. The data do not reproduce the predicted extremely sharp drop in the spin gap at about $g = 0$, the observed minimum being somewhat wider.

It is important to note that the relatively good agreement between our data and the Skyrmion model [Eq. (1)] is achieved by assuming that E_B can be considered as an adjustable parameter. This commonly used procedure (for realistic systems [3,4,15]) remains here phenomenological, and requires theoretical verification in the case of Skyrmion excitations. If this procedure cannot be justified, our data imply that the physical picture of a 2DEG at $v = 1$ is even more complicated and may include excitations which fall beyond both the spin-density wave and Skyrmion models. More theoretical treatment is also required to explain that the observed spin gap shows a rather wide minimum around $g = 0$, instead of the rather sharp drop predicted by the ideal Skyrmion model.

Following the analysis of Schmeller *et al.* [15], the derivative of the measured spin gap with respect to the Zeeman energy $dE_A/d(g\mu_B B)$ can be used to deduce the number of electron spins (s) which are flipped in a single charged excitation. The slope of the long dashed line in Fig. 3 corresponds to $s = 7$ as reported in Ref. [15] in the region $0.01 < g^* < 0.02$ and is in reasonable agreement with our data for $|g^*| > 0.004$. The slope on either side of $g = 0$, $dE_A/d(g\mu_B B) \simeq 33$ (indicated by the long–short dashed line in Fig. 3) suggests that, in the case of the structure investigated, the estimated Skyrmion size λ is of about 33 magnetic lengths in the limit $g \rightarrow 0$.

A purely spin-wave approach predicts that the g-factor dependent changes of the spin-excitation gap are only related to the weak Zeeman term. One may, however, argue whether the prediction [22] that the spin-excitation gap depends additionally on the actual spin polarization of the 2DEG should not modify this conclusion. This prediction was, in fact, the basis for the analysis of previously reported experiments on the excitation spectrum of spin polarized electron gas [3,4]. In such an analysis the measured activation gap is $E_A = g\mu_B B + E_B \frac{(n_\uparrow - n_\downarrow)}{(n_\uparrow + n_\downarrow)}$, where we assume E_B to be an adjustable parameter and $\frac{(n_\uparrow - n_\downarrow)}{(n_\uparrow + n_\downarrow)}$ denotes the spin polarization of the 2DEG. This model implies a temperature dependent activation energy E_A which is constant in the range when $kT \ll E_A$ but rapidly collapses when $E_A \approx kT$. In the latter range the small changes of the g factor may be self-consistently amplified, inducing a variation of E_A stronger than $g\mu_B B$. Our measurements are thermally activated in the limit $kT \leq E_A/4$, and a self-consistent calculation based on the model described in Ref. [22] indicates that, in this temperature range, the difference in spin population $(n_\uparrow - n_\downarrow)$, and hence the spin gap, is independent of temperature. Our calculations indicate that for $kT \leq E_A/4$, assuming a reasonable value of Landau level broadening $\Gamma = 1$ K (deduced from the zero field mobility), the g-factor dependence of E_A is governed solely by the Zeeman term (dashed line in Fig. 3). It is possible to obtain an amplified variation of the spin gap by assuming an unreasonably large broadening $\Gamma \approx 20$ K, but this leads to a gap which is strongly dependent on temperature, in clear contradiction with the experimental fact that the longitudinal resistance shows a well defined activated behavior in the temperature range $kT \leq E_A/4$. In consequence, we find that it is not possible to reproduce the present data within the model proposed in Ref. [22].

In conclusion, we have investigated the variation of the spin activation gap at $\nu = 1$ in the limit of vanishing g factor. The spin activation gap exists even when the Zeeman energy is zero, in agreement with theoretical expectations. The variation of the enhanced spin gap around $g = 0$ is qualitatively consistent with the recently proposed spin-texture excitation model (Skyrmions). The investigated range of the ratio of the Zeeman and Coulomb energies $|g| < 0.01$ seems to be favored by theory. We believe our results will stimulate further theoretical studies verifying in more detail the observed shape of the changes in spin gap versus g factor.

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