Spectroscopic Measurement of Large Exchange Enhancement of a Spin-Polarized 2D Electron Gas

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Exchange enhancements of the spin-polarized 2D electron gas are determined for the first time by inelastic light scattering from spin-flip inter-Landau-level and intersubband excitations. In the magnetic quantum limit $\nu=1$ the splitting between long wavelength magnetoplasmons and spin-flip inter-Landau-level excitations is a direct spectroscopic measurement of the enhanced exchange energy. At $\nu=1$ the enhancements in GaAs quantum wells are in agreement with the Hartree-Fock approximation.

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The high-mobility electron gas in GaAs-AlGaAs heterojunctions and quantum wells reveals new physics due to electron-electron interactions in two dimensions. In large perpendicular magnetic fields and at low temperatures a spin-polarized 2D electron gas exhibits remarkable condensation phenomena, such as the fractional quantum Hall effect and electron solid phases [1,2], driven by electron-electron interactions. In the magnetic quantum limit where all the free electrons are in the lowest spin-split Landau level (with filling factor $\nu=1$) there is a well-known enhancement in the contributions to the g factor from the exchange terms [3,4]. Enhanced exchange should also be important in the incompressible liquid and solid condensed states [1], and in the phase transitions of double layer 2D systems [5]. The exchange enhancement at $\nu=1$ is evaluated within the Hartree-Fock framework [1,4]. Experimentally the enhancement is studied by thermal activation of magnetotransport and band-to-band optical absorption [6,7]. Enhanced exchange may also enter in optical absorption [8]. Such determinations differ significantly from theoretical predictions. The discrepancies are intriguing because the Hartree-Fock theory is expected to account for electron-electron interactions at $\nu=1$. To date, direct spectroscopic methods have not been useful in observing exchange effects. For example, cyclotron resonance excitations in a translationally invariant system are insensitive to electron-electron interactions, as dictated by Kohn's theorem [9]. Similarly, electron spin resonance experiments probe only the long wavelength spin waves which are required to be at the Zeeman energy by Larmor's theorem [10].

This Letter reports the direct spectroscopic measurement of enhanced exchange energies in the spin-polarized 2D electron gas. The determinations are made in GaAs quantum wells by inelastic light scattering from spin-flip excitations. First we show that the time-dependent Hartree-Fock approximation (HFA) predicts at $\nu=1$ long wavelength spin-flip *inter-Landau-level* excitations (SF) that are shifted from the cyclotron energy ω_c by enhanced exchange interactions. This fact, overlooked in previous calculations [11], is the basis for light scattering determinations of enhanced exchange from inter-Landau-level excitations. The shifts from ω_c observed in light scattering spectra of $q\sim 0$ SF modes are the direct measurements of enhanced exchange of the spin-polarized 2D electron gas. Spectra of spin-flip *intersubband* excitations in the magnetic quantum limit also display energy shifts due to exchange enhancement. Calculations within the HFA show excellent agreement with experiment. The results reported here are strong evidence that the Hartree-Fock framework gives a good quantitative description of electron-electron interactions in long wavelength excitations at $\nu=1$. This is in contrast to the determinations based on thermal activations, where the discrepancy between experiment and Hartree-Fock theory is not yet understood. Smaller than expected thermal activation energies could arise from broadening of the electron states in the presence of weak residual disorder [6,12].

In addition to SF modes, we consider magnetoplasmons (MP), the inter-Landau-level excitations without spin flip, and spin waves (SW) associated with spin-flip transitions in the lowest Landau level. The HFA calculation keeps only the leading term in the electron-electron interaction so that coupling to higher-energy excitations is ignored [11,13]. In this approximation the mode dispersions at $\nu=1$ are [11,14]

$$\omega_{\mathrm{MP}}(q)-\omega_c=E_d(q)+E_v(q)+\Sigma_1-\Sigma_0\,, \tag{1a}$$

$$\omega_{\mathrm{SF}}(q)-\omega_c=E_z+E_v(q)-\Sigma_0\,, \tag{1b}$$

$$\omega_{\mathrm{SW}}(q)=E_z+E_v'(q)-\Sigma_0\,, \tag{1c}$$

where $E_z=g\mu_B B$ is the Zeeman energy and E_d is the depolarization or Hartree term (the only one included in the random phase approximation). E_v and E_v' are exchange terms or vertex corrections that account for the excitonic coupling between the excited electron and the ground-state hole. Σ_l is the exchange self-energy of an electron in Landau level l which can exchange with electrons in the occupied level. Σ_1 does not appear in the SF mode because there is no exchange between electrons of opposite spin. The terms due to electron-electron interactions in Eqs. (1) are [11,15]

$$E_d(q) = \tfrac{1}{2} v(q) q^2 e^{-q^2 l_0^2/2}, \tag{2a}$$

$$E_v(q) = -\int \frac{d^2k}{2\pi} v(k) \left(1 - \frac{k^2 l_0^2}{2}\right) e^{i(\mathbf{q}\times\mathbf{k})\cdot\hat{\mathbf{z}} l_0^2} e^{-k^2 l_0^2/2}, \tag{2b}$$

$$E_v'(q) = -\int \frac{d^2k}{2\pi} v(k) e^{i(\mathbf{q}\times\mathbf{k})\cdot\hat{\mathbf{z}} l_0^2} e^{-k^2 l_0^2/2}, \tag{2c}$$

$$\Sigma_l = -\int \frac{d^2k}{2\pi} v(k) \left(\frac{k^2 l_0^2}{2}\right)^l e^{-k^2 l_0^2/2}, \tag{2d}$$

where $l_0 = (\hbar c/eB)^{1/2}$ is the magnetic length, $v(q) = 2\pi e^2 F(q/b)/\varepsilon_0 q$, and b is an inverse length parameter that takes into account the spread of the electron wave function in the perpendicular $\hat{\mathbf{z}}$ direction [4].

In this framework the exchange enhancement of the spin-gap in magnetotransport at $\nu = 1$ is given by the $q \to \infty$ asymptote of the SW mode [6,11]: $\omega_{SW}(\infty) - E_z = -\Sigma_0$. $\omega_{SW}(\infty)$ represents the energy of SW transitions of infinitely separated particle-hole states [11]. For GaAs, $-\Sigma_0 \gg E_z$. The exchange enhancement also occurs in the $q=0$ SF inter-Landau-level excitation accessible in our experiment. This is apparent in the strict 2D limit, where $b = \infty$ and $F(0) = 1$ [4]. In this case $E_v(0) = \frac{1}{2}\Sigma_0$ and the shift of the $q=0$ SF mode is $\omega_{SF}(0) - \omega_c = E_z - \frac{1}{2}\Sigma_0$. The $q=0$ MP mode is not shifted from ω_c, as can be seen from Eqs. (1) and (2).

The measurements are made in asymmetric GaAs-$Al_xGa_{1-x}As$ single quantum wells. They have width $d \sim 250$ Å, Al concentration in the range $0.14 < x < 0.22$, and are modulation doped with Si donors in the top barrier. A ^{3}He cryostat with silica windows for optical access was inserted in the cold bore of a superconducting magnet. Accessible sample temperatures are in the range 0.4 K $\leq T \leq$ 1.8 K. The spectra were excited with cw tunable dye lasers and recorded with optical multichannel detection. Incident photon energies are resonant with excitonic transitions. Power densities were in the range 10^{-4}–10^{-2} W/cm^2. We used the conventional backscattering geometry for 2D layers in which light propagates along the direction of the perpendicular magnetic field. In this geometry there is a small in-plane component of the scattering wave vector $k < 10^4$ cm^{-1}. Under wave-vector conservation $q = k \sim 0$. Inter-Landau-level excitations are parity forbidden in the dipole approximation [16], but mixing between valence subband states will result in a significant scattering cross section. The excitonic transitions in the resonant enhancement originate from valence states close to the first excited heavy subband, for which mixing with light-hole states is known to be significant [17]. Residual disorder which accounts for magnetoroton spectra also plays a role [18].

Figure 1(a) shows spectra of inter-Landau-level excitations at $\nu = 0.98 \simeq 1$. Very weak features that shift with incident photon energy are luminescence. Intersubband excitations, not shown, are in the energy range 22–24.5 meV. The marked dependence of the light scattering intensities on incident photon energy is due to the sharp resonant enhancements. Figure 1(b) shows the mode dispersions calculated with Eqs. (1) and (2). The two stronger light scattering peaks in Fig. 1(a) are assigned to $q \sim 0$ modes that obey wave-vector conservation. One is the MP mode at $\omega_c = 13.8$ meV. The strongest one, at 17.5 meV, is assigned to the SF excitation. The assignment is supported by the agreement with the calculated value of $\omega_{SF}(0)$ shown in Fig. 1(b). The lack of a correct

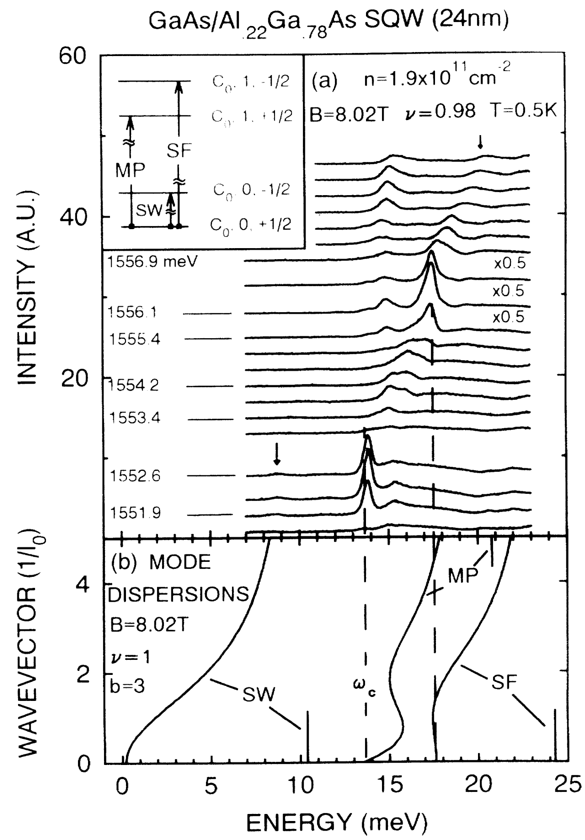

FIG. 1. (a) Resonant light scattering spectra of inter-Landau-level excitations at $B = 8.02$ T and $\nu = 0.98$. The incident photon energies are given in meV. The vertical arrows indicate the weakest features. Inset: A schematic representation of single-particle transitions in magnetoplasmons (MP), spin-flip inter-Landau-level excitations (SF), and spin waves (SW). The states are labeled by a subband index C_i, a Landau-level index $l = 0, 1$, and a spin index $S_z = \pm\frac{1}{2}$. States with $S_z = +\frac{1}{2}$ are lower because in GaAs $g < 0$. (b) Mode dispersions calculated in the time-dependent HFA. The vertical bars indicate the asymptotic energies for $q \to \infty$.

HFA calculation prevented the identification of the SF modes in previous work [18]. The weaker structures between ω_c and $\omega_{SF}(0)$ are due to the magnetoroton density of states of MP modes. They are observed because of the breakdown of wave-vector conservation caused by residual disorder [18].

Spin-flip modes are also observed in spectra of intersubband excitations. Figure 2(a) shows results from a low-density sample in the field range $1 \le \nu \le 2$. For $\nu = 2$ the high-energy peak is the singlet state of charge-density excitations (CDE). At lower energy we find the triplet state of spin-density excitations (SDE). The Zeeman splitting between the components of the triplet (0.06 meV) is not resolved. These features are identical to those measured at $B=0$ [19]. With increasing B the CDE energy does not change. The peaks of SDE have very different behavior. They broaden and shift as seen in Fig. 2(a). The energy shifts are mostly due to the enhancement of the contributions from exchange. At $\nu = 1$ the intersubband excitations are neither singlets nor triplets. The SDE are collective modes derived from transitions with $\Delta S_z = -1$ shown in the inset to Fig. 2(a). The transitions in CDE have $\Delta S_z = 0$.

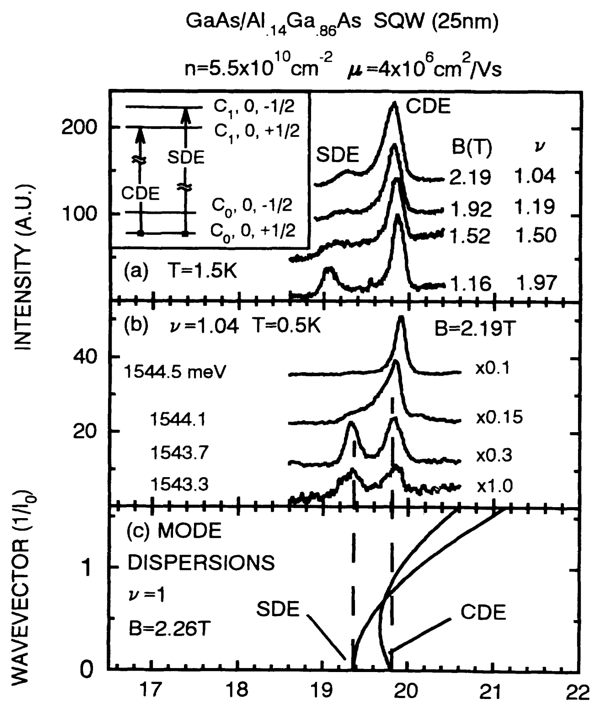

FIG. 2. (a) Inelastic light scattering spectra of intersubband excitations in the field range $1 < \nu < 2$. Inset: A schematic representation of single-particle transitions in SDE and CDE collective excitations. The states are labeled as in Fig. 1(a). (b) Resonant spectra at $\nu = 1.04$. The incident photon energies are given in meV. (c) Mode dispersions calculated in the time-dependent HFA.

The calculations shown in Fig. 1(b) consider the spread of the electron wave function in the perpendicular direction with the parameter b (in units of $1/l_0$). The excellent agreement with experiment is particularly significant because b is not an adjustable parameter. In the model used here, based on a variational wave function for the ground state of the asymmetric quantum well, $b = [48\pi m^* e^2 n/\varepsilon_0 \hbar^2]^{1/3}$ [4]. The value $b=3$ is appropriate for a density $n = 1.9\times10^{11}$ cm^{-2}. Similar agreement is found for several samples with densities in the range $(1.8\text{–}2.5)\times10^{11}$ cm^{-2}.

The blueshifts of the SDE peaks in Fig. 2(a) are manifestations of exchange enhancement in intersubband transitions. These collective excitations are shifted from the subband spacings shown in the inset to Fig. 2(a) by exchange self-energy terms and vertex corrections [4]. The blueshift means that the enhancement of the exchange self-energy is not canceled by the variation in vertex corrections. The energies of CDE are independent of B for $\nu \lesssim \frac{1}{3}$. This shows that changes in exchange self-energies, vertex corrections, and the depolarization effect, the three terms associated with electron-electron interactions [4], cancel out for this mode. This interpretation is supported by calculated mode dispersions shown in Fig. 2(c). The calculation uses the time-dependent HFA [20], and to simplify the computation it assumes that the quantum well is symmetric. This introduces a slight error ($\sim$2 meV) in the single-particle subband spacing but gives an accurate evaluation of electron-electron interactions. The dispersions in Fig. 2(c) have been adjusted by a constant shift to match the energy of CDE at $q=0$. The calculation gives an excellent fit to the splitting between the two modes.

The agreement of exchange enhancements measured in $q\sim0$ spin-flip excitations with HFA calculations is in marked contrast with the results of activated magnetotransport. In the latter determinations exchange enhancements fall well below the HFA predictions [6]. The discrepancy is intriguing because self-energies are q independent. It is possible that effects of residual disorder, which reduces interactions [6,11], may not be apparent in the case of $q\sim0$ excitations [11,21]. This is seen in Eq. 2(b) for the SF mode, where the reduction in Σ_0 might be compensated by a change in the vertex correction.

Long wavelength spin excitations are also sensitive to electron-electron interactions in the extreme magnetic quantum limit. Measurements of intersubband excitations at fields $\nu < 1$ reveal that SDE shift to higher energy and broaden considerably for $\nu \sim \frac{1}{3}$. SF inter-Landau-level excitations are also found to broaden for $\nu < 1$. These changes cannot be attributed to effects of illumination in light scattering experiments [22]. In relatively narrow wells with $d \sim 250$ Å we find that illumination does not cause significant changes either in electron density or in magnetotransport. The light scattering intensities become increasingly weaker for $\nu < 1$ and have very sharp (∼1 meV) resonant enhancement profiles.

In conclusion, using inelastic light scattering we have carried out the first spectroscopic study of exchange enhancement in the spin-polarized electron gas of GaAs quantum wells. At $\nu=1$ there is excellent agreement with the time-dependent Hartree-Fock approximation. The light scattering method allows studies of exchange interactions as a function of electron density and quantum well width. Further research in the extreme magnetic quantum limit offers an opportunity to probe the regimes of the incompressible liquid and solid condensed states. To interpret experiments in these regimes, where the HFA is not applicable, we require a theoretical framework for spin excitations. A single-mode approximation could be applicable here [23].

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