Origin of the anomalous spin resonance in a strongly correlated electron system

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We study the origin of the anomalous spin resonance detected electrically in a strongly correlated two-dimensional electron system. Such resonance reveals itself around nominally nonmagnetic even filling factors ν of the integer quantum Hall effect and is a consequence of strong electron-electron interactions. We directly demonstrate that while the spin resonance at odd ν manifests itself as an increase in the longitudinal resistance of the two-dimensional channel induced by the usual heating due to the radiation absorption, the anomalous resonance around even fillings is detected as a drop in the resistance, as if the electron system is cooled. In contrast, if the magnetic field is tilted so that the ground state of the system becomes ferromagnetic at even ν, the spin resonance around even fillings turns to a more conventional "heating"-like behavior. Analysis of both the evolution of the spin resonance with increasing tilt angle and the measured temperature dependencies allowed us to put forth a possible mechanism of anomalous spin resonance around even fillings that qualitatively explains all of the puzzling experimental findings.

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I. INTRODUCTION

The physics of strongly correlated low-dimensional electronic systems remains a focal point of the modern condensed matter research. Although most of the theoretical ideas were put forward almost a century ago [1–3], these concepts have been experimentally realized only recently [4,5], leaving much room for further investigations. Such a delay was mainly caused by the exceptionally stringent requirements on the purity of the electron system, as the decent transport characteristic as well as the exceptional homogeneity of the system should be retained at ultralow electron densities. Naturally, low densities keep the energy of the electron kinetic motion small compared to the correlation energy and, as a result, greatly enhance the many-electron phenomena. For example, spontaneous spin polarization of the two-dimensional (2D) electron system occurs [4–6] if the ratio of the characteristic Coulomb energy to the Fermi energy reaches a value as large as ∼40.

The other possibility to "freeze" the kinetic motion of the electrons is to apply the large magnetic field perpendicular to the plane of the 2D system, as the magnetic field imposes the Landau quantization on the energy spectrum of the electrons. In this case, samples of even a rather average quality reveal vivid many-particle physics, namely, the fractional quantum Hall effect [7,8] including states at fillings with even denominators [9], Wigner crystallization at subunity filling factors [10], and Stoner-like ferromagnetic phase transition at even fillings [11,12].

Strictly speaking, the Landau quantization was deduced in the limit of noninteracting electrons, i.e., when the characteristic correlation energy $e^2/\epsilon l_b$ is much smaller than $\Delta_c = eB/m^*$—the gap between the Landau levels. Here ϵ is the dielectric constant, $l_b = \sqrt{\hbar/eB}$ stands for the magnetic length, and B is the magnetic field. The symbols m^* denote single-particle electron mass. Exactly this regime is realized in most common GaAs/AlGaAs quantum wells, as the effective mass of electrons in GaAs is small, keeping the cyclotron gap larger than the correlation energy. From the theoretical point of view, under such conditions the e-e interactions act like a small perturbation and a rather straightforward perturbation approach may be used [13,14].

In contrast, some of the semiconductor material systems boast of the large values of m^* that lowers the gap between Landau levels, so that the many-particle correlations contribute significantly to the physics of the system. For example, the electron mass in a ZnO/MgZnO heterojunction typically reaches the value of $0.3m_0$ and is almost an order of magnitude heavier than in GaAs-based quantum wells. At the magnetic field of 10 T the characteristic Coulomb energy may be estimated as 150 K, whereas cyclotron and Zeeman splittings are 40 and 10 K in such structure, respectively. Large mass of electrons inevitably complicates the theoretical description of the system leaving only rather limited theoretical approaches based on exact diagonalization [15–17], guessing the screening functions [18] or phenomenological renormalization of band parameters [11,12]. As a result, many of the beautiful effects observed experimentally are still poorly understood. One such puzzle is the nontrivial spin properties of the strongly correlated two-dimensional electron system both at small magnetic field [4] and in the regime of quantum Hall effect (QHE) [19,20]. The present paper aims to considerably extend the experimental knowledge by probing the spin properties of the two-dimensional electron system by means of electron spin resonance (ESR), in the case that many-particle correlations dominate the characteristic energy associated with the kinetic motion of electrons.

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The spin physics of a strongly correlated two-dimensional electron system (2DES) has already been probed by ESR previously, yielding a number of important experimental insights. The spin resonance of conduction electrons hosted at Si/SiGe quantum wells was studied around ferromagnetic states at even fillings [21]. In wide AlAs quantum wells the spin relaxation of electrons [20] and nuclei [22,23] was examined by means of ESR in the regime of integer and fractional quantum Hall effect. The spin nature of the phase transition observed around even fillings was proved with the aid of ESR in Ref. [24]. The properties of the spin domains formed around ferromagnetic transition were studied in Ref. [25]. Spin-orbit interaction was characterized by measuring the renormalization of the single-particle spin splitting at low fields [26] and in the quantizing limit [27,28]. Surprisingly, even in the nominally unpolarized states formed at even fillings (far from the ferromagnetic phase transition) the spin resonance of conduction electrons was observed [19]. This anomaly is further investigated in more detail in the present paper allowing us to achieve substantial progress in understanding this puzzle.

First of all, we reveal the physical nature of the key distinction between spin resonance signals observed at odd and even fillings. We directly show that ESR at odd ν manifests itself as an increase in the longitudinal resistance of the 2D channel implying the heating of the 2DES due to the resonant radiation absorption. Such behavior is usual and well understood. In contrast, the unconventional spin resonance around even fillings is detected as a deep in sample resistance, as if absorbing radiation results in the cooling of the system. Furthermore, we report that the "sign" of the ESR amplitude depends on the tilt angle so that at large θ when the system becomes ferromagnetic at even fillings, ESR demonstrated conventional "heating" behavior both at odd and even filling factors. Analysis of both the evolution of the ESR with θ and with increasing temperature allowed us to put forth a realistic mechanism of anomalous spin resonance around even fillings that qualitatively explains all of the reported experimental peculiarities.

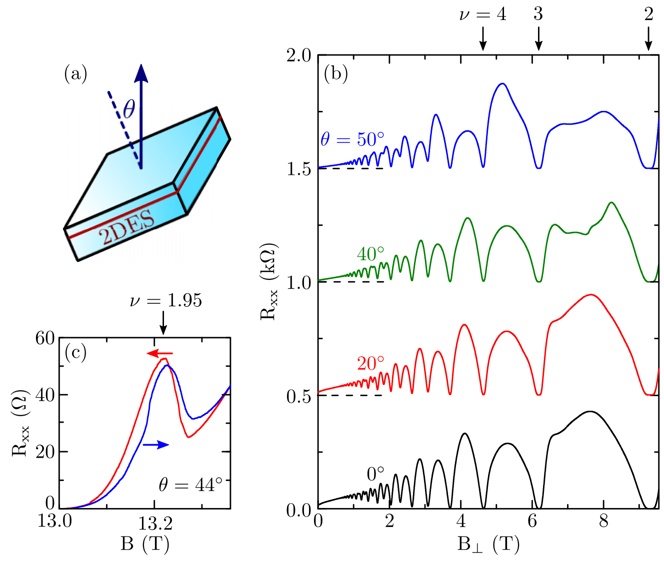

FIG. 1. (a) Schematic representation of the sample and its orientation with respect to the external magnetic field. The sample is tilted at an angle θ between the total magnetic field and the sample surface normal. (b) Magnetic field dependencies of the sample longitudinal resistance in the regime of the QHE for $\theta = 0°, 20°, 40°$, and $50°$. The position of the first several fillings ν are indicated. The curves are shifted upward for clarity. (c) The spike in sample resistance associated with the ferromagnetic phase transition. The tilt angle θ was equal to $44°$. The blue and red curves represent data recorded with different directions of the magnetic field sweeps.

II. EXPERIMENTAL METHOD AND SAMPLES

The experiment was carried out on the ZnO/MgZnO heterojunction hosting a high-quality two-dimensional electron system [29]. The sample was grown by molecular beam epitaxy. The quantity of Mg in the barrier region determines the polarization mismatch at the interface and, as a result, sets the electron density of the 2DES. The low-temperature density and mobility of the sample studied were 4.5×10^{11} cm^{-2} and 250×10^3 cm^2/(V s), respectively. The sample had a conventional van der Pauw geometry with soldered indium serving as Ohmic contacts.

The measurements were done in a ^{3}He cryostat with a superconducting solenoid. The sample was immersed in liquid ^{3}He, so that we were able to perform ESR spectroscopy at temperatures as low as 0.5 K and in magnetic field as large as 15 T. The ESR was detected by monitoring the longitudinal resistance R_{xx}. The change of R_{xx} due to the radiation absorption was extracted using a standard double lock-in amplifier technique. The first amplifier was tuned to the frequency of alternating current applied from source to drain and measured the signal proportional to the longitudinal resistance of the 2D channel. The second lock-in amplifier was fed the output signal from the first one and was tuned to the frequency of the amplitude modulation of the subterahertz radiation, so that it measured a signal proportional to the variation of R_{xx} due to the radiation absorption. The radiation was transferred to the sample through a cylindrical oversized waveguide. We used a microwave generator coupled with a number of frequency multiplier modules as the sources of radiation.

The sample was mounted on a rotation stage so that we were able to change the tilt angle θ between the normal to the 2DES plane and the external magnetic field [see panel (a) of Fig. 1]. The set of studied angles included $\theta = 0°, 20°, 40°$, and $50°$. Typical dependence of the longitudinal magnetoresistance of the 2D electron channel on the perpendicular component of the magnetic field is depicted in Fig. 1(a) for these values of θ. The positions of the first several filling factors are indicated with arrows. Such choice of θ allows us to follow the behavior of electron spin resonance both in the paramagnetic and in the ferromagnetic state of even fillings; as for the structure under study, the critical θ of the Stoner-like transition is $44°$ around even ν. We have checked this value by analyzing the transport properties of the sample around the filling of 2 in case $\theta = 44°$. In full agreement with previous reports we observe a rigid spike with a clear hysteresis with respect to magnetic field sweep direction as demonstrated in Fig. 1(c). The formation of such transport feature is attributed to the splitting of the electron system in a number of domains with different spin polarization near the phase transition. The

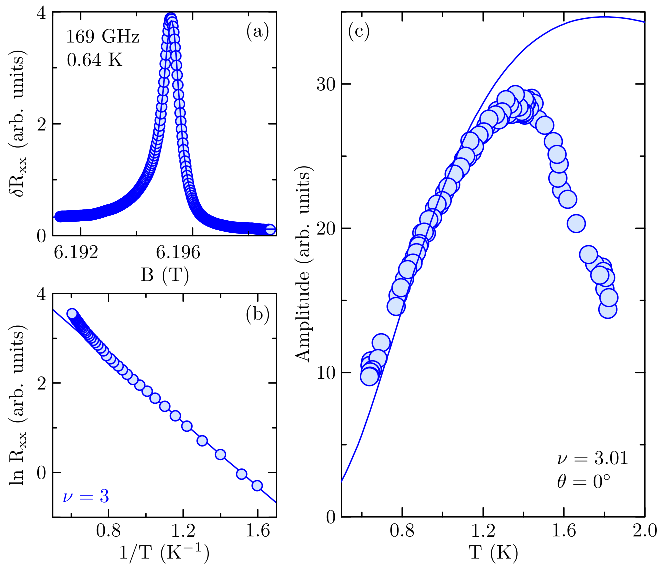

FIG. 2. (a) Typical shape of the ESR peak observed at $\nu = 3$ and $\theta = 0^\circ$. The temperature was 0.64 K. Circles denote the experimental data and the solid line represents the fit. (b) Temperature dependence of longitudinal resistance in the absence of subterahertz radiation at $\nu = 3$. Circles stand for the experimental data, whereas the solid line is the fit with the activation dependence. (c) The temperature dependence of ESR amplitude (circles) at $\nu = 3$. The solid line represents the derivative of the sample longitudinal resistance with respect to temperature at $\nu = 3$.

domain walls greatly enhance the scattering of conduction electrons increasing sample resistance.

III. RESULTS AND DISCUSSION

First, let us examine the behavior of an electron spin resonance at odd filling factors. In this case, the Fermi energy is located exactly in the middle between the two spin-split branches of the highest populated Landau level and the ground state of the system is often referred to as a quantum Hall ferromagnet due to the macroscopically large spin polarization. As always, we observed strong ESR signals around the odd filling factors, namely, $\nu = 3,\ 5$, and 7. The sample ESR line captured around $\nu = 3$ is demonstrated in Fig. 2(a) for the tilt angle $\theta = 0^\circ$ where open circles denote the experimental data and the solid line represents the fit with the Fano-like expression. The amplitude of the resonance was extracted from the fitting procedure.

It is instructional to analyze the behavior of the ESR signal with varying temperature. Typical temperature dependence of the ESR amplitude observed at $\nu = 3$ is depicted in Fig. 2(c). As the temperature is lowered the amplitude of the resonance first grows, reaches maximum at a certain temperature, and then decreases rapidly. Note that similar behavior was observed both for the other odd fillings and for different tilt angles.

To understand the measured temperature dependence let us turn to the description of ESR in terms of spin exciton generation. Electron spin resonance at odd filling factors implies that the absorption of a photon induces the transition of an electron between two spin sublevels of the highest populated Landau level. The excited electron in an upper spin sublevel and the remnant hole in the lower one form a bound state called a spin exciton (or spin wave) [30]. Its dispersion [30] starts from the bare single-electron Zeeman energy, then grows quadratic with the wave vector k and tends asymptotically to the many-particle exchange energy at large k. The total net charge of a spin exciton is zero, so it does not participate in the charge transfer unless its size becomes comparable either with the distance between the sample boundaries, or with the characteristic length of the random potential fluctuations. Such situation may be realized at large k, as the exciton radius raises with growing k due to the Lorentz force. Thus, only spin exciton with large k may contribute to the transport properties of the electron system. A bright illustration of this phenomena is a well-known fact that the gap of the quantum Hall ferromagnet determined from the temperature dependence of the longitudinal magnetoresistance is much larger than the single-particle Zeeman energy [31].

Typically, the wave vector of the subterahertz radiation is negligibly small, so that spin exciton generated during ESR is compact and does not contribute directly to the transport. Yet, these spin waves slowly decay and heat the electron system; as a result, the temperature of the 2D channel resonantly rises and we observe ESR as a peak in the sample resistance R_{xx} [32,33]. Then, the intensity of the ESR is determined by the sensitivity of R_{xx} to increasing T. The dependence of R_{xx} at QHE minima obeys the activation law $e^{-\Delta/2k_BT}$ where Δ is the activation gap, as illustrated in Fig. 2(b) for the case of $\nu = 3$. Here the circles stand for the experimental data and the solid line is a fit using the above written equation. The derivative of this R_{xx} with respect to temperature is shown in Fig. 2(c) by a solid line. As can be seen, the low-temperature behavior of both the derivative $\delta R_{xx}/\delta T$ and the ESR amplitude are similar. Note that the ESR amplitude was normalized to match $\delta R_{xx}/\delta T$. To put it simply, the decrease of ESR amplitude with temperature at low T is due to the fact that the 2DES resistance becomes insensitive to heating as T goes down [34].

At higher temperatures the dependencies of ESR amplitude and $\delta R_{xx}/\delta T$ on T do not coincide. We attribute such behavior to the fact that the spin-lattice relaxation time depends on temperature, so that at higher temperatures part of the generated spin excitons decay before they transfer their energy to the large k part of the spin excitons ensemble and, thus, the effectiveness of “heating” is lowered.

Now let us turn to a much more puzzling ESR behavior observed at even fillings. We would like to underline that at tilt angles smaller than the critical value of 44° the ground state of the system is believed to be spin unpolarized and ESR should not be detected. Yet, a strong spin resonance signal has been reported earlier at even ν [19]. Furthermore, the ESR amplitude detected using a double lock-in technique had opposite signs at odd and even filling factors. This fact is illustrated in Figs. 3(a) and 3(b) where we show the normalized ESR signal detected at $\nu = 4, 6, 8$ and $\nu = 3, 5, 7$.

While the sign change of the ESR amplitude is clearly the key to understanding the phenomenon of intense ESR at even fillings, extra experimental effort was needed to reveal the physical nature of this feature. To eliminate any ambiguities

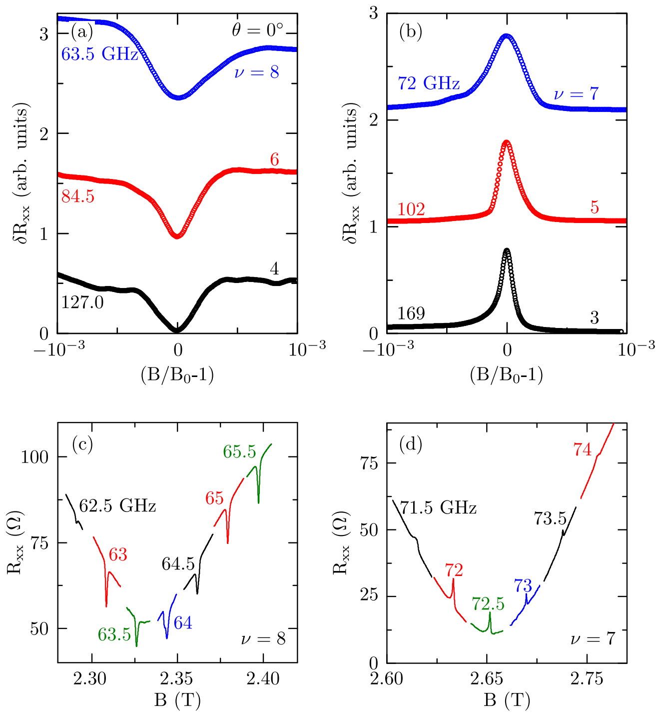

FIG. 3. Typical ESR peaks measured at various even and odd filling factors. (a),(b) Variation of the 2DES resistance δR_{xx} measured using a double lock-in amplifier approach at $\theta = 0^\circ$ for even fillings $\nu = 4, 6, 8$ and odd ones $\nu = 3, 5, 7$, respectively. The curves are shifted upward for clarity. For each curve the magnetic field is normalized by the value B_0—the resonant magnetic field of each ESR line. (c),(d) ESR lines measured using a single lock-in amplifier for a set of frequencies in the vicinity of the filling factors $\nu = 8$ and $\nu = 7$, respectively. The radiation frequencies are indicated near each curve.

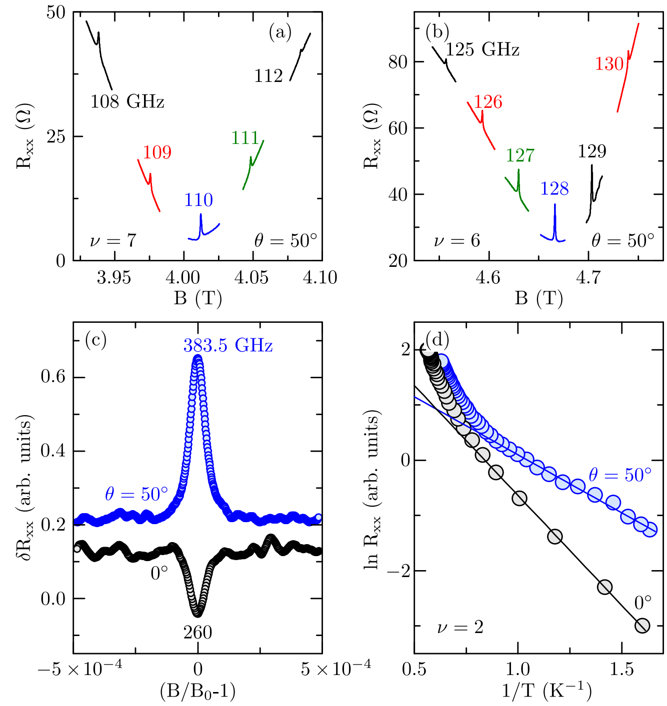

FIG. 4. (a),(b) Typical ESR resonance peaks measured using a single lock-in amplifier around $\nu = 7$ and 6, respectively. The tilt angle θ was equal to 50°. Corresponding radiation frequencies are denoted near each ESR peak. (c) ESR measured at $\nu = 1.95$, $\theta = 0^\circ$ and $\nu = 2$, $\theta = 50^\circ$. The magnetic field was normalized for each peak by its resonant magnetic field. Corresponding radiation frequency is indicated near each curve. (d) The temperature dependence of sample longitudinal resistance around $\nu = 2$ for $\theta = 0^\circ$ and 50°. Solid lines represent the fit with the activation dependence.

brought about by the use of the double lock-in detection, we tried to measure ESR by directly monitoring the longitudinal resistance of the sample with the aid of a single lock-in amplifier. Such approach offers a much worse signal-to-noise ratio. Typical ESR peaks observed in such a manner are shown in Figs. 3(c) and 3(d) for the case of even $\nu = 8$ and odd $\nu = 7$, respectively. The frequency of subterahertz radiation used is indicated near each trace. The off-resonant envelope background corresponds to the typical R_{xx} behavior around QHE minima. Note that heating the 2DES results in the increase of the sample resistance at the QHE minima and, vice versa, cooling the electron system leads to the reduction of the sample resistance. Now the difference between spin resonance observed at odd and even fillings becomes obvious. At $\nu = 7$ ESR manifests itself as an increase of R_{xx} and corresponds to heating of the 2DES. In contrast, at $\nu = 8$ the sample resistance is decreased at ESR implying that the electron system is "cooled" despite the fact that it absorbs the subterahertz radiation. Such peculiar behavior may indicate the formation of a nonequilibrium population of electron states that do not participate in the charge transport and will be discussed later in more detail.

The sign of the ESR amplitude shows a distinct dependence on the tilt angle at even fillings. For the filling factors $\nu = 4$, 6, and 8 the ESR has anomalous negative sign for all θ studied that are less than the critical angle $\theta_c = 44^\circ$. In contrast, for $\theta = 50^\circ$ ESR demonstrates a more conventional positive amplitude. This experimental observation is illustrated in Figs. 4(a) and 4(b), where we demonstrate the ESR peaks measured using a single lock-in amplifier at $\nu = 7$ and $\nu = 6$. Clearly, ESR manifests itself as a heating peak in the sample resistance at both ν. This finding has an important implication: checking the sign of ESR allows one to distinguish easily between the paramagnetic and ferromagnetic states of the integer QHE at arbitrary tilt angles. Note that at odd fillings ESR retains its usual positive sign at all tilt angles.

The situation at $\nu = 2$ is slightly more complicated, but qualitatively the same. In this case ESR could not be detected at the exact $\nu = 2$ at $\theta = 0^\circ$; however, spin resonance with negative amplitude emerges if the electron system is tuned from $\nu = 2$. This fact is illustrated in Fig. 4(c), where we demonstrated the ESR signal detected by the double lock-in scheme for $\nu = 1.95$ and $\theta = 0^\circ$. If we come closer to the ferromagnetic phase transition, i.e., at $\theta = 20^\circ$ and 40°, ESR was not detectable in a vast vicinity of $\nu = 2$ at 0.5 K. This fact is consistent with previously reported data [25] for small electron density samples, where the ground state of the system is close to the phase transition even at $\theta = 0^\circ$. In contrast, if we increase the tilt angle above the critical θ of the ferromagnetic phase transition, ESR appears even at exact $\nu = 2$ and

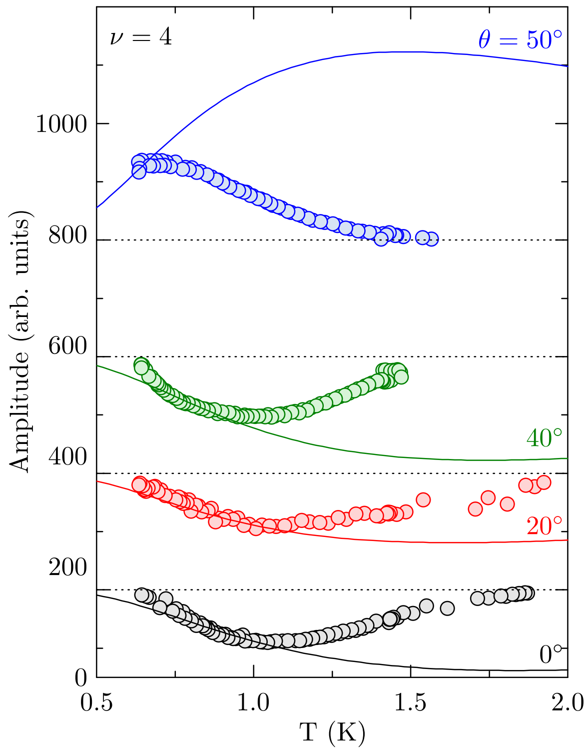

FIG. 5. Temperature dependence of the spin resonance amplitude at $\nu = 4$ for $\theta = 0°, 20°, 40°$ (before the ferromagnetic phase transition) and for $\theta = 50°$ (after the phase transition). Circles denote the experimentally measured resonance amplitude, and solid lines represent the first derivative of the 2DES longitudinal resistance with respect to T. The values of $\delta R_{xx}/\delta T$ were derived from the independently measured temperature dependencies of sample resistance. For convenience, values of $\delta R_{xx}/\delta T$ were multiplied by -1 for $\theta = 0°, 20°, 40°$, and ESR amplitude was normalized to match the $\delta R_{xx}/\delta T$ dependence.

has positive amplitude, i.e., demonstrates conventional heating behavior. The spin resonance peak is depicted in Fig. 4(c) for the case of $\theta = 50°$ and $\nu = 2$. In Fig. 4(d) we show the temperature dependencies of R_{xx} at $\nu = 2$ for $\theta = 0°$ and $50°$. They both follow the standard monotonic activation behavior in both cases, so that sign change of the ESR amplitude may not be attributed to any change in the behavior of R_{xx} with varying T at different tilt angles. The activation energy for the case of $\theta = 0°$ and $50°$ is different mainly due to the fact that the ground state at $50°$ is much closer to the ferromagnetic phase transition. Note that such transition is accompanied by the Landau level crossing.

To better understand the change in the ESR behavior with θ, we have examined the temperature dependencies of the resonance amplitude at even fillings. Typical behavior of the spin resonance observed at $\nu = 4$ is demonstrated in Fig. 5 for a set of tilt angles $\theta = 0°, 20°, 40°$, i.e., before the ferromagnetic phase transition and one angle $\theta = 50°$ after. Open circles denote the ESR amplitude, whereas solid lines represent the derivative of the sample resistance R_{xx} with respect to T that was measured independently. For angles $\theta = 0°$, $20°$, and $40°$ the values of $\delta R_{xx}/\delta T$ were multiplied by -1 to account for the negative sign of the ESR amplitude. At small angles $\theta = 0°$ and $20°$ the low-temperature part of both spin resonance amplitude and $\delta R_{xx}/\delta T$ dependencies coincide rather well, yet at $\theta = 40°$ the ESR amplitude decays with cooling down at a faster rate, than $\delta R_{xx}/\delta T$. Such behavior is similar to what was observed at $\nu = 2$ highlighting the fact, that approaching phase transition suppresses ESR signal at even fillings. The sign change of the ESR amplitude after the ferromagnetic phase transition is clearly visible as well. At $\theta = 50°$ the ESR amplitude and $\delta R_{xx}/\delta T$ demonstrate opposite temperature dependencies. While spin resonance becomes more and more intense, as the temperature goes down, $\delta R_{xx}/\delta T$ decreases. We assume that the observed discrepancy has the same origin as the difference in the temperature behavior of the ESR amplitude and $\delta R_{xx}/\delta T$ at elevated temperatures at $\nu = 3$. Since the ferromagnetic ground state at $\nu = 4$ is less rigid than at $\nu = 3$, one would expect the ESR amplitude to follow $\delta R_{xx}/\delta T$ at temperatures lower than those in case $\nu = 3$ and those experimentally available to us at the present moment.

To explain the reported anomalous ESR behavior, we would like to start with analyzing the excitation spectra of strongly correlated electron systems at even fillings, studied both theoretically [18] and experimentally with the aid of inelastic light scattering [17] for the case of ZnO/MgZnO heterojunctions. It was revealed [17] that in the case of a paramagnetic state at even $\nu = 2N$ the so-called cyclotron spin-flip excitation (CSFE) is the lowest in energy. Such modes are excited when the electron is transferred from the highest occupied Landau level with index N to the $N + 1$ level with a flip of its spin. These transitions associated with the CSFE creation are illustrated in Fig. 6(a) in case $N = 0$. The excited electron and the remnant hole form a bound state.

The CSFE is a triplet state and its dispersion contains three branches [30] separated by the exact single-particle Zeeman splitting, namely, $E(k) = \Delta(k) + \Delta_c - \Delta_z \delta S_z$ where Δ_c and Δ_z stand for cyclotron and Zeeman energy. The value of δS_z is equal to ± 1 or 0. Note that the $\delta S_z = 0$ mode is a linear combination of the ± 1 excitations. The term $\Delta(k)$ denotes the many-particle contribution to the CSFE spectrum. As there are no symmetry limitations imposed on $\Delta(k)$ at zero wave vector, the value of $\Delta(0)$ was reported to be nonzero and even negative [13,14] ensuring that the CSFE modes are the lowest in energy around even fillings. Furthermore, this many-electron correction leads to the formation of the roton minimum [17] in the CSFE dispersion at nonzero wave vectors $k \sim 1/l_b$. Typical dispersion of the two lowest CSFE modes with $\delta S_z = +1$ and 0 is shown in Fig. 6(c). Note that for the typical experimental conditions the Zeeman splitting is around 100 GHz—the value at least an order of magnitude larger than $k_B T$ for $T = 0.5$ K. As a result, under thermal equilibrium and without external exciting radiation only the lowest CSFE branch is occupied. We would like to highlight that generating a CSFE implies a flip of a spin and, thus, substantial population of only the lowest CSFE branch at finite temperatures implies a nonzero spin polarization of the electron system. Then, the spin-flip transitions indicated in Fig. 6(b) become possible allowing the observation of ESR around even fillings.

Now let us turn to the possible mechanism of anomalous ESR detection at even fillings. First, we argue that only CSFE

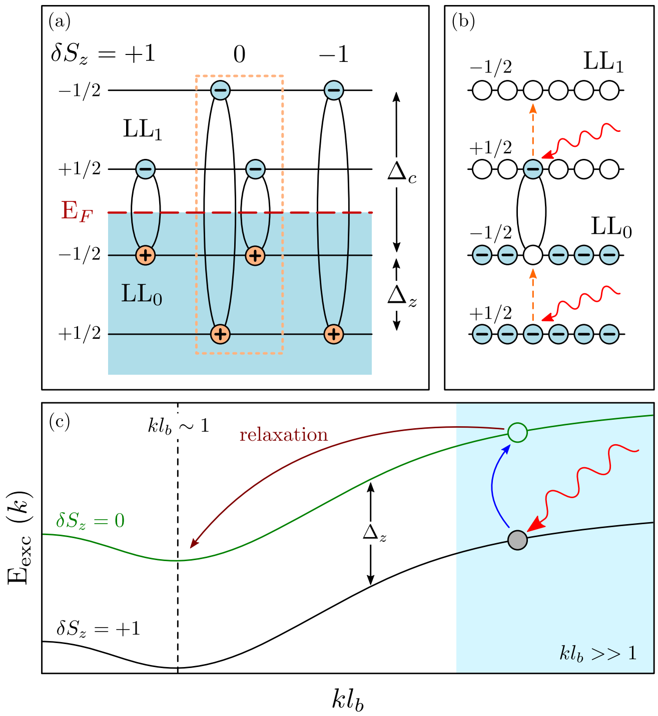

FIG. 6. (a) Schematic representation of the cyclotron spin-flip excitations with $\delta S_z = \pm 1$ and 0 from the ground state. The lowest spin-split Landau level LL_0 is filled. The values Δ_z and Δ_c stand for the Zeeman and cyclotron splittings. (b) The possible spin-flip transitions (marked by dotted arrows) between the partially empty LL_0 and partially occupied LL_1 in the presence of the lowest CSFE mode. (c) The schematic representation of the cyclotron spin-flip excitation dispersion. Two lowest branches with $\delta S_z = +1$ and 0 are depicted.

modes with essentially large wave vector k may contribute to the charged transport. The reasoning for this is essentially the same, as in the case of spin excitons and 2D channel resistance at odd filling factors. Both spin exciton at odd ν and CSFE around even fillings share the same key properties—charge neutrality and dependence of their size on the wave vector because of the Lorentz force. Thus, compact long-wavelength excitations of such type do not participate in charge transfer, yet the situation changes when their wave vector (and, hence, their size) becomes large enough, so that the constituent electrons and holes are almost unbound. The region of k where cyclotron spin-flip excitations may participate in charge transfer is highlighted in Fig. 6(c). Decreasing the amount of CSFEs with large wave vector leads to the disappearance of some of the almost unbound electrons and holes that may take part in scattering processes. As a result, dissipation in the electron system is reduced and 2DES resistance drops. This happens, for example, if we cool the sample and, as a result, sample resistance at exact fillings decreases according to the activation law with the activation gap determined by the exchange-mediated CSFE energy at large k.

If we now apply external radiation with energy tuned in resonance with Zeeman splitting, we will force the electron spin-flip transitions indicated in Fig. 6(c). In terms of CSFE, absorption of a photon transfers a cyclotron spin-flip mode from the lower branch to the upper ones. Conservation laws dictate that such transitions are accompanied by the change of the excitation spin projection by one and no additional gain in excitation wave vector.

The redistribution of CSFEs between branches in the region of small k does not affect the sample resistance, as discussed above. However, the situation is completely different in the range of large k. As the spin relaxation is an extremely slow process at low temperatures and in large magnetic fields [35], the excited CSFE will have enough time to lose excessive k and energy and to reach the roton dispersion minimum before its spin is flipped and it can relax back into its initial lower branch. Thus, the resonant absorption of subterahertz radiation drives the CSFE ensemble into a new quasiequilibrium state with a reduced amount of excitations with large k. As discussed above, this should lead to the decrease of the sample resistance in agreement with the reported experimental observations. To put it simply, resonant absorption of radiation forces the thermally excited almost unbound CSFE to be accumulated around the roton minima of the upper CSFE branches and to become more compact. Note that cooling of the sample is not needed for such redistribution to happen and the overall temperature of the 2DES is most probably increased under radiation absorption. Further studies of this phenomena may lead to the achievement of a macroscopic population of the roton minima and, in perspective, it may lead to the Bose-Einstein condensation of these excitations and, possibly, to the development of highly coherent subterhertz radiation sources. However, at the present moment due to the lack of subterhertz sources with enough output power, we were not able to reach this regime.

If we increase the tilt angle, the system approaches the ferromagnetic phase transition around even filling factors. The nucleating domains of the ferromagnetic phase emerge close to the transition, and their presence enhances the spin relaxation of the nonequilibrium CSFEs allowing them to flip their spin at a much faster rate. This will allow a large portion of excited CSFEs to relax back to their initial branch without any significant change of their wave vector and, thus, to remain in the range of wave vectors where CSFEs participate in the charge transfer, acting against the anomalous mechanism of ESR detection described above. This conclusion agrees well with the experimentally observed behavior of the anomalous ESR.

At large angles, when the ground state of even filling factors becomes ferromagnetic, the excitation spectra are changed [12]. The lowest in energy excitation is spin exciton at both even and odd fillings. As a result, the mechanism of ESR detection should switch to a conventional heating one. Exactly such behavior was captured experimentally.

Another important point we would like to discuss is the absence of anomalous ESR in conventional and thoroughly studied GaAs-based 2D electron systems. The thing is, both the effective mass and the Landé factor $g = -0.44$ are several times smaller in GaAs than in ZnO (around $0.3m_0$ and 1.95, respectively). Under typical experimental conditions single-particle spin splitting in GaAs is much smaller than the thermal energy $k_B T$, hence, all three branches are almost equally populated resulting in negligible spin polarization of the electron system that prohibits observation of ESR. If we cool the system down so that k_BT is smaller than Δ_z, then all of the CSFE modes would be frozen. Note that the amount of CSFEs with large k is governed by thermal activation with activation energy larger than $\Delta_c - \Delta_z \gg \Delta_z > k_BT$ in this case, as the Zeeman single-particle splitting is almost two orders of magnitude smaller than the cyclotron gap in GaAs. A negligible amount of CSFEs prohibits the observation of anomalous ESR according to the mechanism described above. For comparison, in ZnO the ratio between the cyclotron and spin splittings is less than 3.

IV. CONCLUSION

The origin of the anomalous electrically detected spin resonance in a strongly correlated two-dimensional electron system was studied. Anomalous ESR is observed around nominally nonmagnetic even filling factors ν of the integer quantum Hall effect and is clearly due to the strong electron-electron interactions. We show that while ESR at odd ν manifests itself as an increase in the longitudinal resistance of the 2D channel induced by the usual heating due to the radiation absorption, the anomalous resonance around even fillings is detected as a resonant drop of the sample resistance, as if the electron system is cooled. In contrast, if the magnetic field is tilted so that the ground state of the system becomes ferromagnetic at even ν, the spin resonance around even fillings switches to a conventional heating mechanism. Analysis of both the evolution of the spin resonance with increasing tilt angle and the measured temperature dependencies allowed us to put forward a possible mechanism of anomalous spin resonance detection around even fillings. This model qualitatively explains all of the puzzling experimental findings reported in the paper.

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