



Article Spin Transport in a Quantum Hall Insulator

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Abstract: A novel experimental optical method, based on photoluminescence and photo-induced resonant reflection techniques, is used to investigate the spin transport over long distances in a new, recently discovered collective state—magnetofermionic condensate. The given Bose–Einstein condensate exists in a purely fermionic system ($\nu = 2$ quantum Hall insulator) due to the presence of a non-equilibrium ensemble of spin-triplet magnetoexcitons—composite bosons. It is found that the condensate can spread over macroscopically long distances of approximately 200 µm. The propagation velocity of long-lived spin excitations is measured to be 25 m/s.

Keywords: spintronics; spin transport; excitations; low-dimensional systems; spectroscopy; the Bose–Einstein condensate



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1. Introduction

The growing interest in spintronics [1,2] has been incited by the prospect of building fast, energy-efficient devices utilizing the electron spin. In particular, there has been rapid development in magnonics [3], which uses spin waves to transport information [4,5]. Magnonic systems are free of many disadvantages of electronic systems associated with energy dissipation. To accomplish dissipationless transport, it is possible to create the hightemperature Bose–Einstein condensation of magnons in yttrium–iron–garnet films [6,7]. An even more innovative idea for the spin transfer is to include vortex-like spin structures (skyrmions) into the spin dynamics. There have been reported experimental studies involving the manipulation of skyrmions, measuring their mass and velocity [8]. Hence, it is expected that dissipative spin transport can be realized in a skyrmion system. This paper investigates other promising candidates for spin transport similar to magnons, the long-lived spin excitations in a Hall insulator.

In Hall insulators, electron excitations are called magnetoexitons, analogous to magnetoexcitons in semiconductors [9–11]. One of the simplest examples is a magnetoexciton formed by an excited electron at the first Landau level and a Fermi hole at a completely filled zero Landau level at the filling factor v = 2. In the excitation spectrum of a Hall insulator, two types of magnetoexcitons appear—a spin-singlet with the total spin S = 0 and a spin-triplet with the total spin S = 1 [9–11]. Kohn's theorem states that the spin-singlet exciton's excitation energy is equal to the cyclotron energy [12]. At the same time, the excitation energy of the spin-triplet exciton is lower than the cyclotron energy by the value of Coulomb coupling due to electronic correlations in the electron has the same mass and charge as the effective Fermi hole. Since the local spatial density of electrons does not change, the transfer of spin excitons cannot be attributed to either charge or mass transfer. Thus, it has to be associated only with the energy and spin transfer.

The spin-triplet exciton, unlike the spin-singlet exciton, is optically inactive ("dark" exciton). However, a non-equilibrium ensemble of spin-triplet excitons can be created

by optically exciting conduction-band electrons and valence-band holes to higher energy states [14]. The primary means of altering the spin of an electron system is to flip the spin of a photoexcited hole using the strong spin-orbit interaction in the valence band of GaAs. Consequently, when electrons from the zero Landau level recombine with a photoexcited hole in the valence band, the photoexcited electron system changes its spin. The relaxation of spin-triplet excitons to the ground state is accompanied by simultaneous changes in the orbital and spin quantum numbers of the electron system, along with the emission of a cyclotron photon. However, since such conditions are forbidden in the dipole approximation, it leads to an extremely long (~1 ms) lifetime of triplet excitons at low temperatures. On the other hand, the recombination times of a photoexcited hole are much shorter—approximately 100 ps in the heterostructures under study. Therefore, using photoexcitation, it is possible to achieve an enormous density of non-equilibrium spin excitations with an integer spin in a fermionic system to produce a magnetofermionic condensate. In the presented work, we explore the Bose–Einstein condensation of spintriplet magnetoexitons in a v = 2 quantum Hall insulator using photoluminescence (PL) and photo-induced resonant reflection (PRR) techniques.

2. Materials and Methods

The experimental study was carried out on two high-quality heterostructures with single symmetrically doped 31-nm GaAs/AlGaAs quantum wells. For samples 1 and 2, electron concentrations in the two-dimensional channel were, respectively, 1.8×10^{11} cm⁻² and 2.1×10^{11} cm⁻², with dark mobility exceeding 1.5×10^{7} cm²/V·s. Symmetric doping was necessary to minimize the penetration of the wave function of conduction electrons into the barrier, as well as to reduce the effect of the random potential at the interfaces between quantum wells and barrier impurity states on the relaxation of excited electrons. The sample heterostructures were enclosed in a liquid ³He cryostat, placed inside an additional ⁴He cryostat with a superconducting solenoid.

All optical measurements were taken in the temperature range from 0.45 to 1.5 K in the presence of a magnetic field of up to 6 T, using a double-fiber technique (Figure 1b). One fiber carried the laser diode radiation for non-resonant pumping of magnetoexitons simultaneously with the resonant pumping from a tunable narrow-band laser. The other fiber was used to collect the resonant reflection signal from the pumping spot and register the photoluminescence response. Then, the same fiber guided both signals to the entrance slit of a grating spectrometer equipped with a cooled CCD camera or the silicon avalanche photodiode in photon-counting mode connected to a time-gated photon counter to study the kinetics of resonant reflection. In these experiments, the pump/probe spot size diameter was approximately 1.5 mm. A broadband laser diode with an excitation wavelength of 780 nm and a spectral width of 10 nm was used as an optical source to produce spin excitations and a photoluminescence signal. For the resonant reflection source, we used a semiconductor tunable narrow-band "TOptica" laser with a spectral bandwidth of 1 MHz.

We note that the resonant photoexcitation does not lead to the formation of magnetoexcitons. However, there is a spectral overlap between the resonant reflection and photoluminescence signals. Therefore, the resonance excitation was turned off at the time of recording the photoluminescence spectra. Conversely, to suppress the background signal due to the non-resonant light reflection from the sample surface, a pair of crossed linear polarizers were placed between the heterostructure and the ends of the fibers. Since electrons in a magnetic field absorb and emit circularly polarized radiation, the useful signal component of resonant reflection from the 2DES passes through the linear polarizer before entering the probing fiber. At the same time, the non-resonant signal reflected from the sample surface and heterostructure layers is filtered out because its linear polarization remains unchanged. In addition to taking measurements using the double-fiber technique, the photoluminescence spectra were recorded independently for an excitation spot of ~20 µm in diameter, at a separation distance of ~200 µm.



Figure 1. (a) PRR spectra of a 2DES (sample 1) in the state of a Hall conductor, v = 1.4, and a Hall insulator, v = 2.0, with (green curves) and without (black curves) non-equilibrium spin excitations. (b) The diagram of the experimental setup with a double-fiber technique. (c) The optical transition scheme for PRR. The zero and the first Landau levels for electrons in the conduction band of an GaAs/ AlGaAs quantum well are designated by 0_e and 1_e , respectively. The zero Landau level for heavy holes is denoted by 0_{hh} .

3. Results and Discussion

Figure 1a shows the resonant reflection spectra for an optical transition between the zero Landau level states of heavy holes in the valence band and zero Landau level states of electrons in the conduction band, measured in a quantum Hall insulator at filling factors v = 2 and v = 1.4. Clearly, when v = 2, there is no PRR signal without photoexcitation. This trivial result indicates that the absorption of resonance radiation with its subsequent re-emission becomes possible only after the appearance of Fermi holes (vacancies) at the zero Landau level. Due to optical transitions associated with the upper spin sublevel of the zero electron Landau level, the PRR signal emerges as the filling factor is dropped to 1.4. Therefore, the PRR signal is unaffected by turning on the laser diode. By contrast, when it comes to the Hall insulator at the filling factor v = 2, switching the laser diode on results in a PRR signal, implying the generation of a macroscopic number of non-equilibrium magnetoexcitons. Using a rectangular pulse generator to modulate the laser diode current, we measured the decay time τ of the resonant reflection signal from the photoexcitation point after the end of the pumping pulse. Thus, we found that an increase in the pumping pulse duration τ_p or the peak power P_p leads to a rise in the number of magnetoexcitons excited in the Hall insulator per pulse. In this case, the pulse repetition time was set to tens of milliseconds, greatly beyond all possible characteristic transient and relaxation processes in the system under investigation.

Figure 2 shows the dependence of the PRR signal decay time τ on the pumping pulse duration τ_p at a constant repetition time T_p . On this curve, we can distinguish three characteristic regions. Region 1 is associated with the low density of non-equilibrium spin excitations, where the PRR signal is weakly dependent on the width of the pumping pulse. In region 2, the decay time of the PRR signal increases by approximately 300 μ s. Finally, in region 3, we observe a sharp drop in the value of τ , which is related to spin excitations escaping the pumping area [14]. At the end of the last region, the relaxation time τ is measured to be 30 μ s. The velocity of spin excitations in the magnetofermionic condensate escaping the excitation spot can be estimated as $\nu \approx d/2\tau$, where d is the diameter of the pumping spot. Considering d = 1.5 mm, the calculated velocity comes to approximately 25 m/s. This result demonstrates that spin excitations have excellent prospects for signal transmission in Hall insulators. However, it should be noted that the resonance reflection

technique does not discriminate between the relaxation of a non-equilibrium magnetoexciton to the ground state and the escape (diffusion) of a magnetoexciton from the pumping spot. A drop in the number of Fermi holes included in magnetoexcitons is observed in both cases. To understand the dependence of the spin excitation dynamics in the excitation area on the number of the pumped excitons, we measured additional PL spectra of a two-dimensional electron gas when non-equilibrium magnetoexcitons were present. These experiments allowed us to determine the generalized momentum distribution function of spin excitations.



Figure 2. Dependence of the PRR signal decay time τ on the pumping pulse duration τ_p , measured at the pump power of 50 μ W for sample 2 (black dots). The insets (left to right) show the shape of the photoluminescence spectra measured for different values of pump pulse duration, $\tau_p = 10 \ \mu$ s, 30 μ s, 100 μ s, and 1000 μ s.

It has been shown in previous studies [15] that, at low concentrations of magnetoexcitons, the photoluminescence spectrum contains two single-particle lines indicating σ - and σ + polarizations of light (top left inset in Figure 2). These lines correspond to the radiative recombination of electrons with spin projections of +1/2 and -1/2 and heavy holes with spin projections of -3/2 and +3/2, respectively. As the density of dark magnetoexcitons increases, the luminescence spectrum undergoes significant changes. There appear two additional lines related to recombination originating from three-particle complexes constructed from a dark magnetoexciton and an extra Fermi hole. When spin projections on the axis of the magnetic field of a Fermi hole within the magnetoplasmon and an additional Fermi hole coincide, a spin-triplet is formed. Otherwise, if the spin projections of the two holes are oppositely directed, it leads to the formation of a spin-singlet.

The singlet-hole state is called "plasmaron" since a photoexcited electron can recombine with one of the Fermi holes, transferring energy and momentum to the new electron-hole pair (plasma oscillations). The plasmaron can be considered as a magnetoplasmon coupled with an extra Fermi hole. The triplet-hole state is known as a "trion". An electron incorporated into a trion cannot engage in plasma oscillations. Furthermore, the trion's energy provides no data about the generalized momentum of the magnetoexciton contained therein, as evidenced by the small dispersion of magnetoexcitons compared to the characteristic width of the trion photoluminescence line. For example, increasing the momentum from zero to the inverse magnetic length changes the magnetoexciton energy by 0.1 meV in comparison with the 0.2 meV characteristic linewidth of the trion. Thus, the information acquired from the trion photoluminescence spectra is similar to that retrieved from the resonance reflection spectra. In fact, the trion line's intensity accounts for the total number of magnetoexcitons in the excitation spot. The PL spectrum of a plasmaron, on the contrary, reveals both the total number of magnetoexcitons and their energy distribution function. This energy function, in turn, denotes the distribution function of magnetoexcitons within the plasmaron based on their generalized momenta at the plasmaron formation time [15].

The insets in Figure 2 illustrate that at low excitation density, the density of magnetoexcitons with considerable momentum is low, and the plasmaron line (Pln) is absent. As the density of spin excitations grows larger, magnetoexcitons with small momentum begin to scatter into the minimum of the dispersion curve, where the intensity of the plasmaron line with magnetoexciton momenta close to the inverse magnetic length increases relative to that of the trion line (T). As a result, the relaxation time of magnetoexcitons in the ground state measured by the PRR becomes longer (region 2 in Figure 2). This is not surprising since, in the process of relaxation into the ground state, spin excitations have to lose both their energy and momentum about the inverse magnetic length. What is most intriguing is the third region in Figure 2, where the PRR signal decay time decreases drastically. Here, the total number of magnetoexcitons excited in the pumping area, detected from the trion line, varies from that of magnetoexcitons with a generalized momentum about the inverse magnetic length, estimated from the plasmaron line. Indeed, we find the former to be increasing, whereas the latter is decreasing. Therefore, we conclude that not all excited magnetoexcitons leave the excitation spot, but only those with a generalized momentum about the inverse magnetic length.

Optical transitions associated with the three-particle complexes signal the appearance of spin-triplet magnetoexitons in the probing region. Therefore, by observing the variation in luminescence spectra, it is possible to detect the arrival of the spin-triplet magnetoexcitons that were formed far away from the probing point and yet were able to overcome such a separation distance. The inset in Figure 3 shows another experimental scheme. This time, a single excitation laser beam is split into the pumping and probing components. Long-lived spin-triplet magnetoexcitons are formed in the photoexcitation spot ~20 μ m in diameter, where their concentration can be manipulated by varying the pump power. Magnetoexcitons arriving at a probing spot separated from the pumping spot by $\sim 200 \ \mu m$ are registered based on the changes observed in the luminescence spectra. Figure 3 shows the luminescence spectra measured in the probing area for different pumping power levels at the excitation area. Data plots display the lines related to single-particle transitions designated by σ - and σ +, as well as the plasmaron (Pln) and trion (T) lines due to the presence of magnetoexcitons in the probing region. We observe that increasing the pumping power at the excitation area leads to a higher intensity of the Pln and T lines, indicating that dark magnetoexcitons from the photoexcitation spot enter the probing area, having overcome the $\sim 200 \ \mu m$ separation distance.



Figure 3. Photoluminescence spectra for sample 2 measured in the probing spot at a different pump power in the excitation spot. The left-hand inset shows the scheme of photoluminescence spectra measurements with the probing spot separated from the pumping spot by ~200 μ m. The right-hand inset shows the photoluminescence spectra measured in the probing spot at P_{pump} = 25 μ W and different temperatures (0.64 and 0.97 K).

In the inset of Figure 3, we plot the dependence of luminescence spectra on the temperature of the helium bath. Here, we can see that as the temperature reaches 0.97 K, the transfer of spin-triplet magnetoexcitons over the distance of 200 μ m comes to a halt. This result agrees with a previous work [16], where it was shown that the transport of magnetoexcitons requires the transition of a non-equilibrium ensemble of magnetoexcitons into a condensed state. However, for the evidence to be fully conclusive, additional measurements are needed at different distances between the pumping and probing spots.

As a result of the experiments with the pumping and probing spots spaced apart, we verify the above considerations concerning the type of magnetoexcitons responsible for spin transport. We find that with rising photoexcitation power density, the plasmaron (Pln) line intensity grows until the integral intensity of the plasmaron line approaches that of the trion line (Figure 4). This means that almost all magnetoexcitons from the pumping spot that reach the probing region have the generalized momentum about the inverse magnetic length. Hence, by subtracting a properly weighed PL spectrum of the equilibrium 2DES from the photoluminescence spectra of the 2DES measured in the probing spot, we can obtain the generalized momentum distribution function of non-equilibrium magnetoexcitons (inset of Figure 4). These distribution functions clearly indicate that magnetoexciton transport involves namely the magnetoexcitons with momenta about the inverse magnetic length.



Figure 4. Photoluminescence spectra for sample 2. (a) Stationary excitation in case when the probing spot is separated from the pumping spot by ~200 μ m: (lower blue curve)— $P_{probe} = 3 \mu W$, $P_{pump} = 0$; (upper green curve)— $P_{probe} = 3 \mu W$, $P_{pump} = 150 \mu W$. The upper inset shows the density distribution of plasmarons with respect to energy (lower scale) and momentum (upper scale) for two stationary excitation modes corresponding to the lower PL spectrum (blue curve) and the upper PL spectrum (green curve). The red curve represents the calculated dispersion of magnetoexcitons according to [17]. (b) Pulsed photoexcitation at $\tau_p = 10 \mu s$, and $P_p = 100 \mu W$. The diagrams show possible optical transitions for two polarizations of radiation.

4. Conclusions

In summary, we propose an experimental optical method of investigating spin transport by "dark" magnetoexcitons in a $\nu = 2$ quantum Hall insulator. We observe a unique phenomenon of long-lived spin excitations propagating over macroscopic distances as large as 200 µm throughout the sample region, with no generated magnetoexitons. The propagation velocity of the spin excitations is measured to be approximately 25 m/s. We also demonstrate that the transmission of the magnetoexciton density over large distances does not involve all magnetoexcitons but only those with the momentum near to the inverse magnetic length. As a result, we propose that magnetoexcitons with the dipole moment approximately equal to the magnetofermionic condensate in a quantum Hall insulator at $\nu = 2$.

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