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Spin excitons and exciton complexes in quantum wells in quantum Hall regime at filling factor of $\nu = 2$

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General work description

Topic relevance. The study of two-dimensional electronic systems is an important task for both fundamental and applied science. Two-dimensional electronic systems based on GaAs/AlGaAs, ZnO, graphene, and dichalcogenides heterostructures are ideal model objects for studying single-and multiparticle effects. In this paper, I focused on the study of photoexcited excitons under the conditions of the quantum Hall effect in AlGaAs/GaAs/AlGaAs heterostructures. Recent research [1, 2, 3] showed the presence of long-living spin excitons and their possible condensation. Experimental investigation of the possible spatial propagation of excitons under optical pumping of a non-trivial form; attempts to detect sound in a dense exciton system textitetc. are interesting not only in themselves but also as part of a wider range of tasks. The answers to these questions are closely related to the possibility of creating condensates with non-trivial statistics. On the other hand, it is linked to an "optical transistor" which is capable of amplifying the light signal due to the nonlinearity of luminescence and resonant reflection from the sample, depending on the pump conditions.

Indeed, the "dark" excitons in the Landau quantization conditions are chosen as the object. Quantum wells with a width of about 30 nm are chosen as a model system since in these wells it is possible to combine a sufficiently large concentration of carriers with a sufficiently large Coulomb interaction and electron mobility. These excitons were first detected in the form of a spin-triplet on even fill factors in the Raman spectra in 2005 in the above system. It was found that the energy of this excitation is slightly lower than the cyclotron energy [1]. It would seem that any excitations between adjacent Landau levels must obey Kohn's theorem [4] and have energy strictly equal to the cyclotron energy. In this paper, it is shown that at different orientations of the electron and hole spins, the condition of the theorem ceases to apply and the decrease in energy can be explained by the Coulomb interaction. Thus, it was shown that this excitation consists of a hole on the upper spin sublevel of Landau directly below the Fermi level and an electron on the lower spin sublevel of Landau above the Fermi level. This exciton also cannot directly decay into a cyclotron photon according to spin conservation law. The measured lifetime of "dark" cyclotron spin excitons reached hundreds of microseconds at a temperature of 0.5 K [2, 3]. The paper [3] also shows the phase transition between two aggregate states of an exciton system. In these works, previously unknown physical phenomena are shown, for the study of which new experiments are required.

Aim The aim of this work is an experimental study of cyclotron spin excitons arising in highly mobile AlGaAs/GaAs/AlGaAs heterostructures in a quantizing magnetic field at the filling factor 2, as well as the study of three-particle complexes including spin excitons.

Novelty:

1. For the first time, lines associated with three-particle complexes of cyclotron spin excitons — trions and plasmarons were detected in the photoluminescence spectra at the fill factor $\nu = 2$. The theoretical estimation of the energy shift of new PL lines from single-particle transitions is carried out.
2. For the first time, a temperature-threshold macroscopic spreading of spin excitons, *i.e.* Bose-Einstein condensation, was detected by direct observation using the resonant photoinduced reflection technique.
3. The spreading of spin exciton condensate is studied using spatially separated pump-probe luminescence.
4. The excited states of the trions are found and their energy is shown to correspond to the theoretical model.

Practical significance The practical significance is determined by the new knowledge obtained about the nature and characteristic features of spin magnetoexitons in a two-dimensional electronic system on the filling factor $nu = 2$. The results of these studies are important not only for a deeper understanding of the physics of the quantum Hall effect, but also for the broader field of Bose-Einstein condensates and their properties.

Methods The studies were carried out using spectral and spatially resolved photoluminescence, spectral and temporarily resolved resonant photoinduced reflection.

Defence statements:

1. Three-particle complexes, plasmarons and trions, have been discovered and studied in the luminescence spectra of two-dimensional electronic systems under the conditions of Landau quantization on the fill factor $\nu = 2$. A numerical simulation of the plasmaron energy is carried out, the result of which is consistent with the experiment.
2. Excited states of trions in the luminescence spectra have been detected. Numerical simulation of intra-trion transitions is performed. The obtained energies are consistent with the experimental data.
3. Macroscopic non-diffusive spreading of magnetofermionic condensate was detected and investigated using the resonant photoinduced reflection technique. According to the results of the experiment, this spreading reaches 400 microns.
4. The spreading of magneto-fermionic condensate was investigated using pump-probe photoluminescence. The result is consistent with previous experiments. In addition, there is evidence in favor of spreading excitons with a specific momentum corresponding to the minimum of dispersion.

Credibility The reliability of the results obtained is ensured by publications in peer-reviewed, highly cited journals. The results are in line with the results obtained by other authors.

Aprobation. The main results of the work were reported to international conferences:

1. International Conference on Optics of Excitons in Confined Systems, Bath, UK, 09/2017. Poster presentation. Replaced by an oral talk due to a delay in obtaining a visa.
2. International Conference on Physics of Light–Matter Coupling in Nanostructures, Chengdu, China 05/2018. Oral presentation
3. International Conference on New Trends in Quantum and Mesoscopic Physics Erevan, Armenia, 06/2018. Oral presentation
4. Universal Themes of Bose-Einstein Condensation, Pittsburgh, USA, 04/2019. Oral and poster presentation

Personal contribution. The author took an active part in setting tasks, developing methods, conducting experiments, constructing theoretical models and performing appropriate calculations, processing and interpreting the results, and publishing articles.

Publications. The main results on the topic of the dissertation are presented in 6 printed publications.

Thesis summary

The **introduction** substantiates the relevance of the research carried out within the framework of this dissertation work, formulates the purpose, sets the tasks of the work, sets out the scientific novelty and practical significance of the presented work. The next chapters describe the literature review, the samples and research methods used, then the results of the study of the properties of spin magnetoexitons and their complexes.

The first chapter is devoted to a review of the scientific literature on the problem under study. A review of the theoretical literature on excitations under the conditions of the quantum Hall effect is given. Kohn's theorem [4] is given that multiparticle effects do not affect the energy of optically allowed cyclotron transition at zero momentum. This energy is exactly equal to the cyclotron energy $\omega_c = \frac{eB}{m^*c}$. Larmor's theorem is given that the energy of a transition with a spin flip at the same Landau level does not depend on multiparticle effects and is exactly equal to the energy of the Zeeman splitting [5]. The properties of the cyclotron spin-flip exciton (CSFE), which does not obey the above theorems, are considered because its energy can be significantly lower than the cyclotron energy. In addition, its dispersion is non-trivial. The energy minimum of the dispersion is found at the momentum $k = l_B$, where $l_B = \sqrt{\frac{\hbar c}{eB}}$ magnetic length [6]. The decay of the magnetoexiton under consideration is not independently possible not only according to the law of conservation of spin, but also according to the law of conservation of momentum, if it is in the energy minimum. This observation

suggested an experiment to measure the lifetime of CSFE [2]. A technique for time-resolved resonant photoinduced light reflection has been developed. According to the measurement results, the lifetime of the CSFE was 50 microseconds. In the following work, the lifetime reached 900 microseconds, and measurements of the lifetime, the intensity of the resonant reflection, the intensity of the resonant reflection and luminescence clearly showed the formation of a new phase — magnetofermionic condensate [3].

The **second chapter** is devoted to samples and experimental methods. The chapter describes the growth method and the parameters of the samples used. The scheme of the experimental setup for light-guide measurements and optical measurements with a spatial resolution is given. Methods of measurement and equipment for measuring luminescence, polarization analysis, measurement of photoinduced resonant reflection with a temporal or spatial resolution are considered.

For the research tasks, high quality of structures was important, so highly mobile samples based on AlGaAs/GaAs/AlGaAs heterostructures were used (Fig. 1). The parameters of the samples used are given in Table. 1.

Table 1 — Samples under analysis

#	μ, $\frac{\text{cm}}{\text{V s}}$	Doping type	d, нм	n_{2d}, cm^{-2}	$\tau_{CSFE}^{\max}$, us
1	5×10^6	one sided	17	$2{,}7 \times 10^{11}$	15
2	20×10^6	two sided	35	$2{,}0 \times 10^{11}$	800
3	20×10^6	two sided	30	$3{,}4 \times 10^{11}$	$<$50

In the case of light-guide measurements, the test sample was mounted on a metal substrate using a conductive silver paste, quartz optical fibers with a diameter of 400 microns were placed near it. To analyze the luminescence, a $\lambda/4$ plate and a linear polarizer were placed sequentially between the sample and the light guide (see Fig. 1). To suppress the reflection from the surface, crossed polarizers were placed between the light guides and the sample.

For measurements with spatial resolution, the sample was mounted in the same way. However, instead of a light guide, the light was focused by a complex lens. The maximum size of the spot on the sample was 20 microns, the field of view was 400 microns. For the analysis of polarization, it was possible to use any desktop equipment.

The **third chapter** is devoted to the observation and study of three-particle complexes — plasmarons and trions. These complexes were detected as satellites of single-particle recombination lines in the luminescence spectra of the samples. The correspondence of satellites and lines was verified by analyzing the circular polarization of luminescence. These lines are related to the bound states of a cyclotron spin exciton and a photoinduced valence hole. The energy (redshift of luminescence) of such complexes may differ slightly from the one-particle energy in

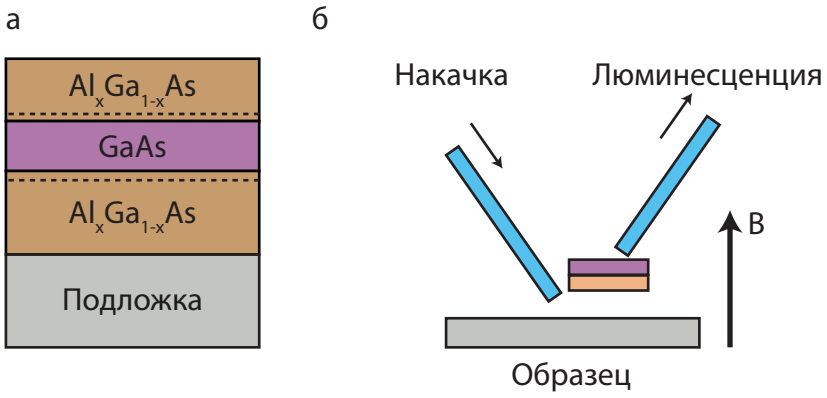

Figure 1 — Figure 2.1:"a" is a diagram of the sample structure. The dotted line indicates the Si-donor layer. "b" is a scheme for the study of circularly polarized luminescence. The $\lambda/4$ plate is indicated in sand color, the linear polarizer is purple.

the case of an ordinary trion, or it may reach 3.5 MeV in the case of a plasmaron. Such a large energy shift is explained by the possibility of an electron at the first Landau level to exchange with a hole at the zero Landau level. A numerical estimate is obtained for the plasmaron energy as the plasmon energy according to the theory from the work [6].

The **fourth chapter** is devoted to the observation of excited states of trion. In the luminescence spectra, luminescence lines were found that lie higher in energy than single-particle transitions. These lines are attributed to transitions within three-particle complexes. A numerical estimate of this energy is obtained using calculations according to the theory [7].

The **fifth chapter** is devoted to the study of the macroscopic spreading of spin excitons from the pump spot using resonant photoinduced reflection and photoluminescence. The first method shows the temperature threshold spreading, the second method — the properties of the condensate in the stationary state are studied.

The main results of the work are given in **conclusion**.

Author's publications on the topic of the dissertation

First-tier publications:

[1] A. V. Gorbunov et al. — "Detection of spin excitation transfer in a two-dimensional electron system via photoluminescence of multiparticle exciton complexes". — In: *JETP Letters* 106.10 (Nov. 2017), p. 682—685. — DOI: 10.1134/s002136401722009x.

[2] V. A. Kuznetsov et al. — "Excited States of Magnetotrion". — In: *JETP Letters* 107.2 (Jan. 2018), p. 96—99. — DOI: 10.1134/s0021364018020091.

[3] A. S. Zhuravlev et al. — "Artificially Constructed Plasmarons and Plasmon-Exciton Molecules in 2D Metals". — In: *Physical Review Letters* 117.19 (Nov. 2016). — DOI: 10.1103/physrevlett.117.196802.

[4] L. V. Kulik et al. — "Long-range non-diffusive spin transfer in a Hall insulator". — In: *Scientific Reports* 8.1 (July 2018). — DOI: 10.1038/s41598-018-29323-8.

[5] V. A. Kuznetsov et al. — "Three-particle electron-hole complexes in two-dimensional electron systems". — In: *Physical Review B* 98.20 (Nov. 2018). — DOI: 10.1103/physrevb.98.205303.

[6] Alexander V. Gorbunov et al. — "Spin Transport over Huge Distances in a Magnetized 2D Electron System". — In: *Annalen der Physik* (May 2019), p. 1800443. — DOI: 10.1002/andp.201800443.

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