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Mixed exciton–plasmon collective elementary excitations of the Bose–Einstein condensed two-dimensional magnetoexcitons with motional dipole moments

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The collective elementary excitations of the two-dimensional (2D) magnetoexcitons in the state of their Bose–Einstein condensation (BEC) with nonzero wave vector $\boldsymbol{k}$ and inplane parallel oriented motional dipole moments are investigated in the Hartree–Fock–Bogoliubov approximation (HFBA). The breaking of the gauge symmetry is achieved using the Bogoliubov theory of quasiaverages and the Keldysh–Kozlov–Kopaev (KKK) method. The starting Hamiltonian and the Green's functions are determined using the integral two-particle operators instead of the single-particle Fermi operators. The infinite chains of equations of motion for the multioperator four- and six-particle Green-s functions are truncated following the Zubarev method and introducing a small parameter of the perturbation theory related with the lowest Landau levels (LLLs) filling factor and with the phase-space filling factor. The energy spectrum of the collective elementary excitations consists of the mixed exciton–plasmon energy braches, mixed exciton–plasmon quasienergy branches as well as the optical and acoustical plasmon energy branches. The exciton branches of the spectrum have gaps related with the negative values of the chemical potential and attractive interaction between the 2D megnetoexcitons with inplane, parallel oriented motional dipole moments. The slopes of the mixed exciton–plasmon branches are determined by the group velocities of the moving condensed excitons in the laboratory reference frame. The acoustical and optical plasmon energy branches are gapless. Their dependence on the small wave vectors accounted from the condensate wave vector $\boldsymbol{k}$ is linear and quadratic, respectively, with saturation in the range of high values of the wave vectors.

1 Introduction The properties of the symmetric two-dimensional (2D) electron–hole (e–h) system, with equal concentrations of both components in a strong perpendicular magnetic field, with coinciding matrix elements of Coulomb electron–electron (e–e), hole–hole (h–h), and e–h interactions have attracted a great deal of attention in the last two decades [1–8]. A hidden symmetry and the multiplicative states were discussed in numerous papers [5, 9, 10]. The collective states such as the Bose–Einstein condensation (BEC) of 2D magnetoexcitons and the formation of the metallic-type electron–hole liquid (EHL) were investigated in Refs. [1–8]. Studying the phenomenon of the BEC has become a milestone in condensed-matter physics [11]. The remarkable properties of superfluids and superconductors are intimately related to the existence of a bosonic condensate of composite particles consisting of an even number of fermions. In highly excited semiconductors the role of such composite bosons is taken on by excitons, which are the bound states of electrons and holes. Furthermore, the excitonic system has been viewed as a keystone system for exploration of the BEC phenomena, since it allows the particle density and interaction to be controlled *in situ*. Promising candidates for experimental realization of such system are semiconductor quantum wells (QWs) [12], which have a number of advantages compared to the bulk systems. The coherent pairing of electrons and holes occupying only the lowest Landau levels (LLLs) has been studied using the Keldysh–Kozlov–Kopaev (KKK) method and the generalized random-phase approximation (RPA) in Refs. [6, 13]. The BEC of magnetoexcitons takes place in a single exciton state with the wave vector $\boldsymbol{k}$, suggesting that the high density of electrons in the conduction band and of holes in the valence band were created in a single QW structure with the size quantization much greater than the Landau quantization. When $\boldsymbol{k} \neq 0$ a new metastable dielectric liquid phase formed by Bose–Einstein condensed magnetoexcitons has been revealed [6, 7]. The importance of the excited Landau levels (ELLs) and their influence on the ground states of the systems was first noted in Refs. [2–5]. The influence of the ELLs of electrons and holes was studied in detail in Refs. [7, 8]. The indirect attraction between electrons (e–e), between holes (h–h) and between electrons and holes (e–h) due to the virtual simultaneous quantum transitions of the interacting charges from LLLs to ELLs is a result of their Coulomb scattering. The first step of the scattering and the return to the initial states were described in the second order of the perturbation theory.

Plasmon oscillations in the one-component system of the monolayer in a strong perpendicular magnetic field were studied by Girvin et al. [14], who proposed the magnetoroton theory of collective excitations for the conditions of the fractional quantum Hall effect (FQHE). The FQHE occurs in the low-disorder, high-mobility samples with partially filled Landau levels with the filling factor in the form $\nu = 1/m$, where m is an integer. Considerable progress has recently been achieved toward understanding the nature of the many-body ground-state well described by the Laughlin variational wave function [15]. Theory of the collective excitation spectrum proposed in Ref. [14] is closely analogous to Feynman's theory of superfluid helium [16]. The main Feynman arguments lead to the conclusions that on general grounds the low-lying excitations of any system will include density waves. As regards the 2D system the perpendicular magnetic field quenches the single-particle continuum of the kinetic energy leaving a series of discrete highly degenerate Landau levels, which are spaced in energy at intervals $\hbar\omega_c$. In the case of the filled Landau level, $\nu = 1$, the lowest excitation is necessarily the cyclotron mode in which particles are excited into the next Landau level, because of the Pauli exclusion principle. In the case of FQHE the LLL is fractionally filled. The Pauli principle no longer excludes low-energy intra-Landau-level excitations. For the FQHE case the low-lying excitations have primary importance, rather than the high-energy inter-Landau-level cyclotron modes [14]. The spectrum has a relatively large excitation gap at zero wave vector $\boldsymbol{k}l = 0$ and in addition it exhibits a deep magnetoroton minimum at $\boldsymbol{k}l \sim 1$, quite analogous to the roton minimum in helium. The magnetoroton minimum becomes deeper with decreasing filling factor ν in the row $1/3$, $1/5$, $1/7$ and this is a precursor of the gap collapse associated with the Wigner crystallization that occurs at $\nu = 1/7$. For the largest wave vectors the low-lying mode crosses over from being a density wave to becoming a quasiparticle excitation [14]. The Wigner crystal transition occurs slightly before the roton mode becomes completely soft. The magnitude of the primitive reciprocal lattice vector for the crystal lies close to the position of the magnetoroton minimum. The authors of Ref. [14] suggested also the possibility of pairing of two rotons of opposite momenta leading to the coupling of two-roton states with a small total momentum, as is known to occur in helium. Contrary to the case of fractional filling factor, the excitations of a filled Landau level in the 2DEG were studied by Kallin and Halperin [17].

Fertig [18] investigated the excitation spectrum of two-layer and three-layer electron systems. In particular the two-layer system in a strong perpendicular magnetic field with filling factor $\nu = 1/2$ of the LLL in the conduction band of each layer was considered. The interlayer separation z and spontaneous coherence of a two-component 2D electron gas were introduced.

Both half-filled layers a and b are accompanied by a substrate with the positive charge, which ensures the electrical neutrality of the system. The half-filled layer a can be considered as fully filled by electrons in the LLL of the conduction band and a half-filled by holes in the same LLL of the conduction band.

The electrons of the fully filled conduction band are compensated by the charge of the substrate and we can only consider the electrons on the layer b and the holes on the layer a. Then, the wave function [18] of the coherent two-layer electron system can be rewritten in the form that coincides with the BCS-type wave function of the superconductor. It represents the coherent pairing of the conduction electrons on the LLL of the layer b with the holes in the LLL of the conduction band of the layer a and describes the BEC of such unusual excitons named FQHE excitons, because they appear under conditions suitable for observation of the FQHE. Here, only the BEC on the single exciton state with wave vector $\boldsymbol{k} = 0$ is considered.

Fertig determined the energy spectrum of the elementary excitations in the framework of this ground state. In the case when $z = 0$ the lowest-lying excitations of the system are the higher-energy excitons.

Because of the neutral nature of the $\boldsymbol{k} = 0$ excitons the dispersion relation of these excitations is to a good approximation given by $\hbar\omega(\boldsymbol{k}) = E_{\mathrm{ex}}(\boldsymbol{k}) - E_{\mathrm{ex}}(0)$, where $E_{\mathrm{ex}}(\boldsymbol{k})$ is the energy of the exciton with wave vector $\boldsymbol{k}$. This result was first obtained by Paquet et al. [5] using a RPA. For $z = 0$ the dispersion relation $\omega(\boldsymbol{k})$ vanishes as $\boldsymbol{k}^2$ for $k \to 0$, as one expects for the Goldstone modes.

$\omega(\boldsymbol{k})$ behaves as an acoustical mode $\omega(\boldsymbol{k}) \sim \boldsymbol{k}$ in the range of small $\boldsymbol{k}$ for $z > 0$, whereas $\omega(\boldsymbol{k})$ tends to the ionization potential $\Delta(z)$ in the limit $k \to \infty$.

In the region of intermediate values of $\boldsymbol{k}$, when $\boldsymbol{k}l \sim 1$, the dispersion relation develops dips as z increases. At a certain critical value of $z = z_{\mathrm{cr}}$ the modes in the vicinity of the minima become equal to zero and are named soft modes.

