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Light absorption properties related to long-living ensemble of spin excitations in an unpolarized quantum Hall system

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The cyclotron spin-flip excitation (CSFE) in the $\nu = 2$ quantum Hall system, being the lowest-energy one [1–3], has an extremely long lifetime. The latter is theoretically estimated to be up to several milliseconds [4]. In fact the CSFE relaxation found experimentally in the unpolarized quantum Hall system created in a real GaAs/AlGaAs heterostructure reaches $100\,\mu$s [5] at finite temperature $T \simeq 0.5\,$K, that seems to be a record value for a delocalized state excited in the conduction-band of mesoscopic systems. Such a slow relaxation suggests that ensemble of the excitations, being a kind of magnetoexcitons [6] and obeying the Bose–Einstein statistics, can experience at sufficiently high concentration a transition to a coherent state – Bose–Einstein condensate. Both the CSFE creation and the CSFE monitoring are performed by optical methods [3, 5]. In this connection, it is interesting to study the contribution to the light absorption related to the CSFE ensemble in the 2DEG. In the present work we perform a comparative analysis of the absorption by the CSFE ensemble in incoherent and coherent phases. (This also strongly correlates with the light emission if the resonant reflection technique is used [5], therefore it is sufficient to consider only the absorption.)

The CSFE is a solution of the many-electron Schrödinger equation with the $\delta S = 1$ change of the total spin as compared to the ground state where $S = 0$ [1]. Generally, this excitation is a triplet with $S = 1$ and $S_z = 1, 0, -1$. All three components have equidistant energies gapped by the Zeeman value $|g\mu_B B|$. The lowest-energy component corresponds to $S_z = 1$ because the g-factor is negative in the GaAs heterostructures. We will consider only these $S = S_z = 1$ magnetoexcitons in our study. A noticeable concentration of such excitations, $N/\mathcal{N}_\phi \lesssim 0.1$ ($\mathcal{N}_\phi$ is the total number of states in the Landau level), can be achieved experimentally [5]. In this letter we study the exciton ensemble only in the "dilute limit", thus ignoring the CSFE-CSFE coupling. Due to the very long CSFE relaxation time we study the exciton ensemble as a metastable system with a given number of excitons N.

It is noticeable that the CSFE represents a purely electronic kind of magnetoexciton [6] where the quantum-mechanical average of distance between positions of an electron promoted to the spin-up sublevel of the first Landau level and an effective "hole" (vacancy in the spin-down sublevel of the zero Landau level) is equal to $\Delta\mathbf{r} = l_B^2\mathbf{q} \times \hat{z}$ [1], where $\mathbf{q}$ is the magnetoexciton wave-vector, $l_B = \sqrt{c\hbar/eB}$ is the magnetic length. Thus this excitation possesses electric dipole-momentum $\mathbf{d_q} = el_B^2\mathbf{q} \times \hat{z}$.

I. Using the "excitonic representation" technique (see, e.g., [7]) we study an incoherent state of the CSFE ensemble:

$$|\mathrm{ini}, N\rangle = \mathcal{Q}^\dagger_{\mathbf{q}_N}\mathcal{Q}^\dagger_{\mathbf{q}_{N-1}}...\mathcal{Q}^\dagger_{\mathbf{q}_1}|0\rangle, \qquad (1)$$

where operator $\mathcal{Q}^\dagger_{\mathbf{q}} = {N_\phi}^{-1/2}\sum_p e^{-iq_x(p+q_y/2)}b^\dagger_p a_{p+q_y}$ (first used in works [8]), acting on the ground state $|0\rangle$, creates a magnetoexciton with 2D momentum $\mathbf{q}$; $|0\rangle$ denotes the $\nu = 2$ ground state with a fully occupied zero Landau level; $a^\dagger_p$ is the operator creating an electron on the upper spin sublevel of the *zero* Landau level with spin-down, i.e., antiparallel to the magnetic field, and $b^\dagger_p$ creates an electron on the *first* Landau level with the spin directed along the magnetic field (here and below p-numbers as well as the wave-vector $\mathbf{q}$ are measured in $1/l_B$ units).

The perturbation operator responsible for the light absorption has the form

$$\hat{\mathcal{A}} = A\sum_p V^\dagger_p a^\dagger_p, \qquad (2)$$

where $V^\dagger_p$ is creation operator of a valence heavy-hole, and A is a certain constant. Operator (2) is uniquely determined by "verticality" of optical transitions conditioned by the inequality $\mathcal{L}k_{\mathrm{photon}\|} \ll 1$, where $\mathcal{L}$ is a characteristic of the electron 2D-density spatial fluctuations and $k_{\mathrm{photon}\|}$ is the photon wave-vector component parallel to the electron system plane. This condition actually is of met [5].

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The action of the $\hat{\mathcal{A}}$ operator on state $|\mathrm{ini}, N\rangle$ results in the $A\sum_i |\mathrm{f}, \mathbf{q}_i\rangle$ sum, where each of N possible final states represents a combination of $N-1$ purely electronic magnetoexcitons with one magnetoexciton formed by a valence hole:

$$|\mathrm{f}, \mathbf{q}_i\rangle = -\hat{\mathcal{X}}_{\mathbf{q}} \prod_{j\neq i} \mathcal{Q}^{\dagger}_{\mathbf{q}_j}|0\rangle. \quad (3)$$

Here $\hat{\mathcal{X}}_{\mathbf{q}} = \mathcal{N}_{\phi}^{-1/2}\sum_p e^{-iq_x(p+q_y/2)}V_p^{\dagger}b^{\dagger}_{p+q_y}$ is the exciton operator which, by acting on the ground state generates the valence hole and the b-sublevel electron. By neglecting any inter-excitonic coupling one finds the transition matrix element squared

$$|M_i|^2 = \langle \mathbf{q}_i, \mathrm{f}|\hat{\mathcal{A}}|\mathrm{ini}, N\rangle^2 \approx |A|^2. \quad (4)$$

Calculation of the relaxation rate is a summation procedure in accordance with the formula:

$$\mathcal{R}_{\mathrm{I}} = \frac{2\pi}{\hbar}\sum_i |M_i|^2\delta(D_{\mathbf{q}_i}) \approx \frac{2\pi|A|^2}{\hbar}\sum_i \delta(D_{\mathbf{q}_i}), \quad (5)$$

where

$$D_{\mathbf{q}} = \hbar\omega + E_{\mathbf{q}} - E_{v-e,\mathbf{q}}, \quad (6)$$

ω is frequency of the probing laser beam, $E_{\mathbf{q}}$ to describe energy of the $\mathcal{Q}^{\dagger}_{\mathbf{q}}|0\rangle$ magnetoexciton, and $E_{v-e,\mathbf{q}}$ to describe energy of the "valence-magnetoexciton" $\hat{\mathcal{X}}^{\dagger}_{\mathbf{q}}|0\rangle$.

The summation (5) depends on the distribution of the quantum numbers $\mathbf{q}_i$ by their possible values in the phase space. When the temperature is low enough (actually at $T < 1\,\mathrm{K}$), this distribution is determined by the presence of a smooth random electrostatic potential in the 2D heterostructure, so every magnetoexciton "gets stuck" at a certain point of the potential energy corresponding to the local minimum. The minimum corresponds to zero group velocity, $\partial E_{\mathbf{q}}/\partial\mathbf{q} = 0$, where the function $E_{\mathbf{q}}$ includes both the q-dispersion of the CSFE determined by the Coulomb coupling in the many-electron system and the electrostatic energy $d_{\mathbf{q}}\nabla\varphi(\mathbf{R})$ associated with the dipole moment of the excitation in the random external field $\varphi(\mathbf{R})$. Our analysis allows to find the rate $\mathcal{R}_{\mathrm{I}} = N\mathcal{K}_{\mathrm{I}}$, where "oscillator strength" $\mathcal{K}_{\mathrm{I}}$ depends on the magnetic field (increasing with the growth of B) and on parameters of the random potential: a characteristic amplitude of its spatial fluctuations (Δ) and a correlation length (Λ). Actual estimates are $\Delta \simeq 5{-}8\,\mathrm{meV}$, $\Lambda \simeq 50{-}60\,\mathrm{nm}$.

II. In the coherent phase, all magnetoexciton have the same wave vector, that is, now the excitonic ensemble has the form:

$$|N\rangle = (\mathcal{Q}^{\dagger}_{\mathbf{q}})^N|0\rangle. \quad (7)$$

Considering this state as initial, we find the action of operator (2) resulting in the final state $|f\rangle = |\hat{\mathcal{A}}|N\rangle = = -AN\hat{\mathcal{X}}_{\mathbf{q}}|N-1\rangle$ which has energy equal to $E_{N-1,\mathbf{q}} + + E_{v-e,\mathbf{q}}$ [$E_{N,\mathbf{q}}$ to designate energy of the coherent initial state (7)]. The square of the matrix element of the transition between the states $|N\rangle$ and $|f\rangle$ (provided their normalization) is

$$|M_N|^2 = \left|\langle\langle f||\hat{\mathcal{A}}||N\rangle\rangle\right|^2 \approx |A|^2N, \quad (8)$$

that is by factor N larger than, e.g., the matrix element (4) (double brackets $||...\rangle\rangle$ denote the normalized states).

If we consider individual domains with areas $d\mathbf{R}$, much smaller than the square of the characteristic scale of the spatial fluctuations of the random potential Λ^2, but much larger than the area of the magnetic flux quantum $2\pi l_B^2$, then the total relaxation rate can be presented as

$$\mathcal{R}_{\mathrm{II}} = \frac{2\pi|A|^2N}{\mathcal{N}_{\phi}\hbar}\int d\mathbf{R}\,\delta(\hbar\omega + E_{N,\mathbf{q}} - E_{N-1,\,\mathbf{q}} - E_{v-e,\mathbf{q}}), \quad (9)$$

where $E_{v-e,\mathbf{q}}$ is again the energy of the "valence magnetoexciton". It can be shown that in the coherent phase all corrections of the first gradient approximation to the energies in the argument of the δ-function in (9) (i.e., proportional to the electric field $\mathcal{E}(\mathbf{R}) = -\nabla\varphi$) mutually compensate each other. The second-order corrections, $\sim\mathcal{E}^2$, are determined only by the $E_{v-e,\mathbf{q}}$ term. This enables us to calculate the relaxation rate, $\mathcal{R}_{\mathrm{II}} = N\mathcal{K}_{\mathrm{II}}$, and estimate the ratio of "oscillator strengths" $\mathcal{K}_{\mathrm{II}}/\mathcal{K}_{\mathrm{I}} \propto B^{3/2}/\mathcal{E}$ (where $\mathcal{E} \sim \Delta/\Lambda$), which numerically under conditions corresponding to the experiment [5] is approximately 10. In other words, in the coherent phase, light absorption/emission in resonance reflection measurements becomes about an order of magnitude more intense than in the incoherent phase.

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