True, quasi and unstable Nambu-Goldstone modes of the two-dimensional Bose-Einstein condensed magnetoexcitons

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(Dated: 12 May 2018)

The collective elementary excitations of two-dimensional magnetoexcitons in a Bose-Einstein condensate (BEC) with wave vector $\vec{k} = 0$ were investigated in the framework of the Bogoliubov theory of quasiaverages. The Hamiltonian of the electrons and holes lying in the lowest Landau levels (LLLs) contains supplementary interactions due to virtual quantum transitions of the particles to the excited Landau levels (ELLs) and back. As a result, the interaction between the magnetoexcitons with $\vec{k} = 0$ does not vanish and their BEC becomes stable. The energy spectrum contains only one gapless, true Nambu-Goldstone(NG) mode of the second kind with dependence $\omega(k) \approx k^2$ at small values k describing the optical-plasmon-type oscillations. There are two exciton-type branches corresponding to normal and abnormal Green's functions. Both modes are gapped with roton-type segments at intermediary values of the wave vectors and can be named as quasi-NG modes. The fourth branch is the acoustical plasmon-type mode with absolute instability in the region of small and intermediary values of the wave vectors. All branches have a saturation-type dependencies at great values of the wave vectors. The number and the kind of the true NG modes is in accordance with the number of the broken symmetry operators.

I. INTRODUCTION

A two-dimensional electron system in a strong perpendicular magnetic field reveals fascinating phenomena such as the integer and fractional quantum Hall effects. The discovery of the fractional quantum Hall effect (FQHE) fundamentally changed the established concepts about charged single-particle elementary excitations in solids [1, 2].

In this paper we study a coplanar electron-hole system with electrons in a conduction band and holes in a valence band, both of which have Landau levels in a strong perpendicular magnetic field. Earlier, this system was studied in a series of papers [3-9] mostly dedicated to the theory of 2D magnetoexcitons. This system bears some resemblance to the case of a bilayer electron system with half-filled lowest Landau levels in the conduction bands of each layer [10]. The coherent states of electrons in two layers happened to be equivalent to the BEC of the quantum Hall excitons [11] formed by electrons and holes in different layers. The system we are interested in has only one layer, with electrons in conduction band and holes in the valence band of the same layer created by optical excitation or by p-n doping injection (both of these methods can be called "pumping"). In the case of a single excited layer which we consider, the density of excitons can be quite low, so that the electron Landau level and the separate hole Landau level are each only slightly occupied, and Pauli exclusion and phase space filling do not come in to play.

II. HAMILTONIAN OF THE BOSE-EINSTEIN CONDENSATION OF MAGNETOEXCITONS.

The effective Hamiltonian describing the interaction of electrons and holes lying on the LLLs is

$$H = H_{Coul} + H_{Suppl}. \tag{1}$$

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