Luminescence of 2D electrons: Wigner crystal or Mahan exciton?

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The ground state of a 2DES (two-dimensional electron system) in the intermediate range of interaction parameter $r_s = me^2/\epsilon\hbar^2\sqrt{\pi n}$ **can be considered as an electron gas, an electron Fermi liquid, or a Wigner crystal**.
Calculations show that electrons at low densities form a triangular lattice, and the spin state of the system can be either a ferromagnet or a spin glass. Crystallization in an ideal system requires very low electron densities ~37 r_s. However, calculations taking into account impurities indicate that the liquid–crystal transition is shifted to a more realistic value of ~7 r_s [1]. It was first stated in [2], that at sufficiently low temperatures defects (vacancies or impurities) in a crystal transform into delocalized excitations that propagate freely through the crystal because of tunneling. Delocalized defects in a crystal may be regarded as quasiparticles and classified by their quasimomentum ***k***.

A vacancion is an excitation in the Wigner crystal in which one electron is removed from the system. The vacancion energy ***E(k)*** assumes values within a band of width ***D*** proportional to the probability of vacancy tunneling.
The spectrum of single-particle excitations for a triangular lattice with interatomic spacing ***a*** in the nearest-neighbor approximation is

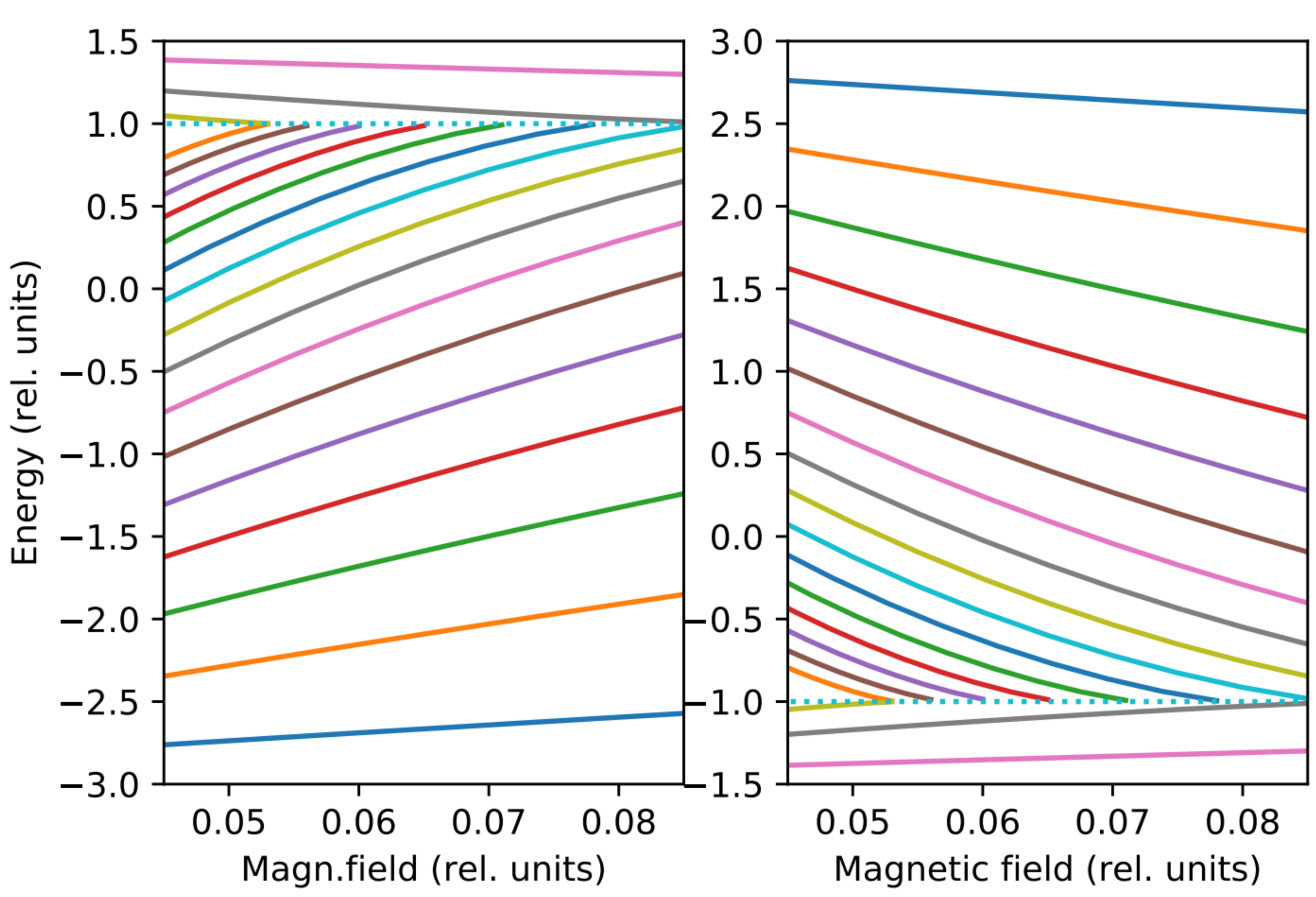
$$E(k) = 2t[\cos(k_x a) + 2\cos(k_x a/2)\cos(\sqrt{3}k_y a/2)]$$

where ***t*** is the hopping integral (tunneling parameter) [3].
The bandwidth is ***D=9|t|.***
The density of states diverges logarithmically as ***E= - 2t***
(a van Hove singularity appears at this point)

The energies of vacancions in a magnetic field E_n
(Landau levels for vacancions) are calculated in the quasiclassical approximatio

$$S(E_n) = \left(\frac{2\pi eH}{\hbar c}\right)(n+\gamma)$$

S(E) is an area for the closed orbit in ***k***-space for ***E(k)=E***. For the energy of singularity there is no closed orbit. Landau levels are calculated for one valley centered at point Γ and for two valleys centered at points K.
Near the extremum points Γ and K the dispersion is squared and $\gamma = 1/2$
It is shown that Landau levels from maximum and minimum sides of the band depend differently on a magnetic field. The energy level inside the band corresponding to the singularity point for the density of states does not depend on a magnetic field. The picture for Landau levels is inverted if the 2D Wigner crystal has changed from the ferromagnetic to the antiferromagnetic state.



Quasiclassical energies of Landau levels for vacancions in 2D Wigner crystal as functions of magnetic field.
Energy unit is **2|*t*|.** Magnetic field unit is H_0, for H_0 the filling-factor $\nu = 1$
Dashed line corresponds to the energy of singularity.
Left ***t*** **< 0** (ferromagnetic).
Right ***t*** **> 0** (antiferromagnetic).

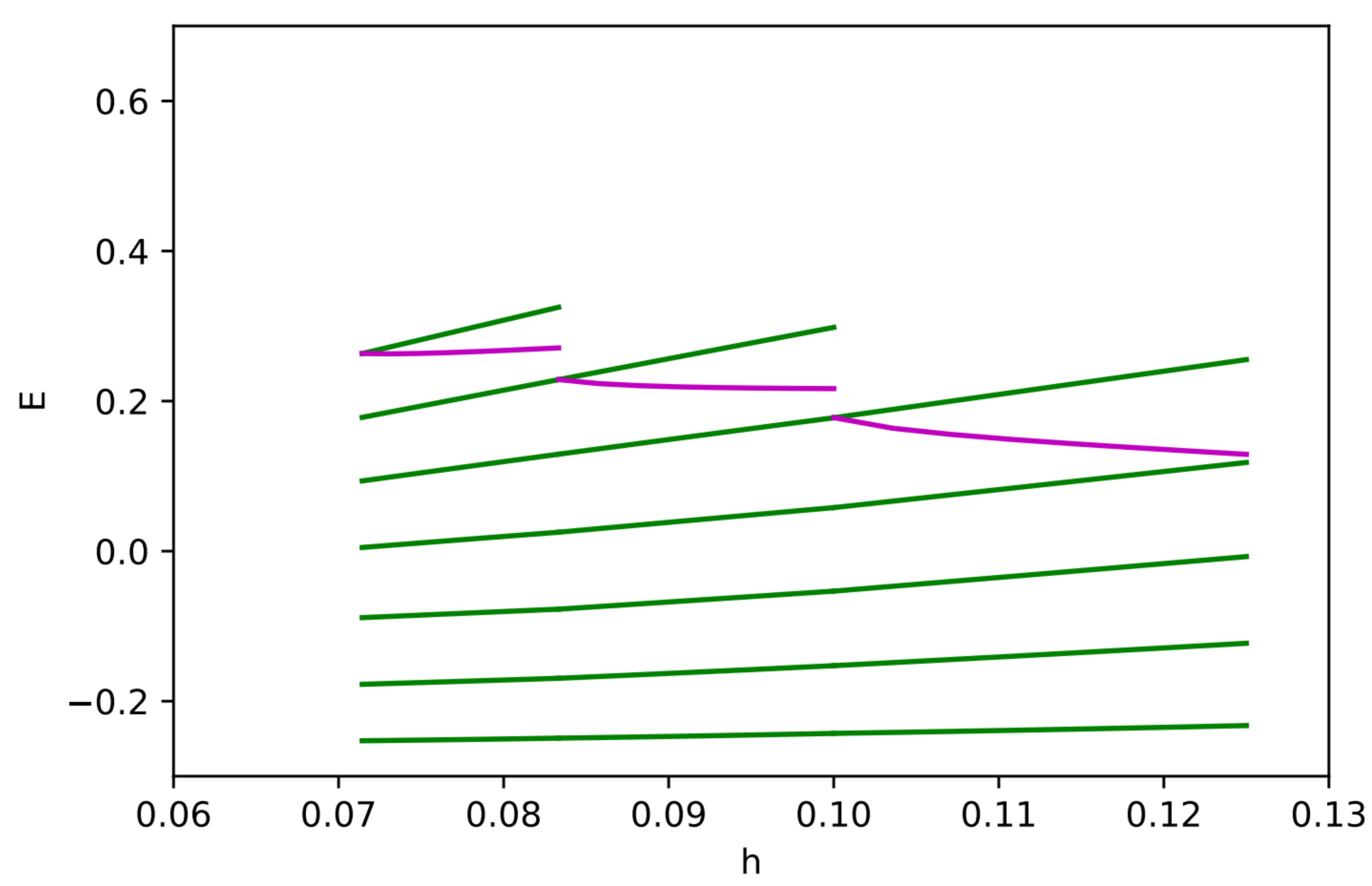
High-quality MgZnO/ZnO heterojunctions have emerged as an excellent object for the study of electron-electron interaction effect in 2DES. The values of the interaction parameter r_s up to 10 are readily achieved. The photoluminescence spectra from the two-dimensional electrons (2DES) confined at MgZnO/ZnO heterojunction at r_s~6 are studied [4]. Electrons annihilate with the localized valence-band holes, and a quasiholes appear in 2DES. For the lower-density samples well defined lines from Landau levels depend unusually on magnetic field. In [4] this behaviour is connected with the phenomenon of the Mahan exciton [5].

Mahan exciton is the strong enhancement of the photoluminescence intensity towards the electron Fermi energy E_F due to multiple electron-hole scattering processes to states above E_F .
The optical spectra of highly excited quantum wells are calculated by solving the Bethe-Salpeter equation for the e-h pair Green's function within the statically screened ladder approximation. This singular integral equation describes the multiple scattering of electrons and holes via the statically screened Coulomb interaction.

The luminescence shape without magnetic field allowed both explanations: Wigner crystal and Mahan exciton. As it is considered in the work [6], the shape of the luminescence band of the Wigner crystal is determined by the vacancion dispersion, the density of states ***N(E)*** and the damping of vacancions. The width D corresponds to the width of the photoluminescence band. The luminescence intensity will feature a maximum near the singularity point

In this work the Mahan exciton effect for 2D electron gas in magnetic field is considered. The unusual behavior of luminescence lines in high magnetic field takes place es for 2D Wigner crystal as for taking into account Mahan exciton. For 2D Wigner crystal the Landau levels for vacancions (quasiholes in WC) depend differently on magnetic field from maximum and minimum sides of the band.

For the Mahan exciton and Landau levels in RPA approximation there is different behavior in magnetic field. Mahan exciton energy is lower in higher magnetic field opposite to dependence for landau levels.



Energies of Landau levels (green) and Mahan exciton (purple) in 2D electron gas in RPA approximation as functions of magnetic field.
Energy (**E**) unit is cyclotron energy $E_c(H_0)$.
Magnetic field (**h**) unit is H_0, for H_0 the filling-factor is 1.

[1] S.T. Chui and B. Tanatar. Phys. Rev. **B** 74, 458 (1995).
[2] A.F. Andreev and I.M. Lifshitz, Soviet Physics JETP 29, 1107 (1969).
[3] M. Avignon, V.N. Men'shov, and V.V. Tugushev. Physics of the Solid State **43**, 563 (2001).
[4] V.V. Solovyev and I.V. Kukushkin, Phys. Rev. **B** 96, 115131 (2017).
[5] S. Schmitt-Rink, C. Ell and H. Haug. Phys. Rev. **B** 33, 1183 (1986).
[6] V.E. Bisti. JETP Letters 109, 109 (2019).