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The basic state of two layered heterostructure at high magnetic field

S. V. Iordanski[1)]

Landau Institute for Theoretical Physics of the RAS, 142432 Chernogolovka, Russia

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It is shown that the electron states in the two layered heterostructure at high magnetic field (when it is possible to neglect Coulomb interaction) can be classified by the energy levels of the size quantization. We construct the basic electron state when the electron states with the lowest energy of the size quantization have the density of the half filled Ll. That defines the electron chemical potential and gives the possibility to describe the wave functions of all electrons including the energy distribution of the two dimensional part. That gives the electron distribution consistent with the experimental results S. Luin et al., Phys. Rev. Let. **94**, 146804 (2005).

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Two layered heterostructures are the objects of the intensive experimental and theoretical works more then two decades of years (see e.g. [1]). The most interesting is the case when the layers are close enough to observe interlayer interaction. The initial theoretical works use the simplified model [2] where the layer number is treated as an additional pseudo spin index for 2d electrons. But the experimental work [3] has shown the inconsistency of this approach for the description of the electron energy distribution by direct measurements. Therefore one must reconsider the problem of the basic state for two layered heterostructures at high magnetic field. In this short note I develop an alternative approach close to the base notions for one layered systems.

It is well known that the existence of quasi 2d systems require the separate action of the in plain coordinates $\mathbf{r}$ and the residual normal coordinate z. We shall consider strong magnetic field when the kinetic energy term proportional to the magnetic field B is large compare to Coulomb interaction proportional to $\sqrt{B}$. As it was shown in [4] in that case any electron state constructed from the states of the first Ll is thermodynamic unstable to the creation of the vortex lattices decreasing the electron free energy. Therefore the hamiltonian kinetic energy term must include not only the external magnetic field but also the contribution of the periodic vortex lattice.

But the heterostructure construction suggests also that the action of the coordinate z normal to the (xy) layer plain can be separated and the form of the electron wave function is given by the product

$$\psi(z,\mathbf{r}) = Z(z)\Phi(\mathbf{r}). \qquad (1)$$

This requirement is not valid for Coulomb interaction proportional to $1/\sqrt{r^2+z^2}$ but is valid for the interaction with the plain vortex lattice arising due to thermodynamic instability. Therefore we have two separate Shroedinger equations:

$$i\hbar\frac{\partial Z}{\partial t} = \frac{1}{2m_e}\left(-i\hbar\frac{\partial}{\partial z}\right)^2 Z(z) + U(z)Z(z) \qquad (2)$$

and

$$i\hbar\frac{\partial \Phi}{\partial t} = H(\mathbf{r})\Phi, \qquad (3)$$

where operator $H(\mathbf{r})$ include the interaction with the external magnetic field and the vortex lattice. The wave functions Z and Φ include different energetic factors $\exp[-iEt/(\hbar)]$ with the total electron energy $E = E_z + \epsilon(\mathbf{p})$ where $\epsilon(\mathbf{p})$ is the energy of the in plain motion and E_z is the energy of the size quantization connected with the potential $U(z)$. As usual it is convenient to introduce electron chemical potential μ defining the border of the filled states $E \le \mu$. For one layered system the first equation gives the unimportant shift of the total electron energy $E = E_0 + \epsilon(p)$ where E_0 is the basic energy of size quantization. But for two layered system the process of the electron states filling may be more complicate depending on the structure of the two dimensional spectrum $\epsilon(p)$ and the electron chemical potential μ.

Let us start from the half filling of the Ll density and suppose the hexagonal symmetry of the vortex lattice with two vortices of the lowest circulation in the unit cell. In this case as was shown in [5] the representation of the space group for the Eq. (3) inevitable has two dimensional representation in two points of Brillouin cell boundary of the reciprocal lattice (see [5]) $\mathbf{k}_0 = (k_0^x, k_0^y)$ and $\mathbf{k}_0' = (k_0^x, -k_0^y)$ here $k_0^x = 2\pi/3a$ and $k_0^y = 2\pi/3\sqrt{3}a$ where a is the length of the period in the vortex lattice.

[1)]e-mail: iordansk@itp.ac.ru

If the electron chemical potential is equal to the energy at these points all states with the negative energy $E_0 + \epsilon(p) - \mu < 0$ will be filled and we shall have Dirac spectrum with the zero mass in the vicinity of $\mathbf{k}_0$ and $\mathbf{k}'_0$. But this is valid in two layered system only for the electrons with the total energy $E_0 + \epsilon(p)$ for $\mathbf{p}$ in the Dirac cone with the lowest energy. For the next level of the size quantization $E_1 > E_0$ the filled states are only at $E_1 + \epsilon(p') < \mu$ and the apex of the low energy Dirac cone is empty

$$\epsilon(p') \leq E_0 - E_1. \tag{4}$$

Thus we find the electron state for the two layered system which has the lowest electron energy at the electron chemical potential equal to the energy in the Dirac point.

We suppose the condition (4) is satisfied by the electron spectrum. In the opposite case the situation does not differ essentially from the case of one layer. But the real experiments [2] suppose large enough barrier between the layers. That gives the small difference between the first two levels of the size quantization: the lowest symmetric and the next antisymmetric in layers number. The experimental results [3] define the energy of electrons which have the maximal light absorption. The theory based on the quasi spin description of two layered systems give this energy equal the energy difference $E_1 - E_0 = \Delta_{\mathrm{SAS}}$ in the disagreement with the experiment [3] giving approximately $1/3$ of this quantity. In our model this phenomenon has a simple explanation. The light absorption require the transitions from the occupied electron states $E < \mu$ to the unoccupied electron states $E > \mu$. The filled electron states with the energy $E_1 + \epsilon_{p'} \leq \mu$ have the transitions to the empty states with $E_1 + \epsilon(p) > \mu$ in the direction to the Dirac point. But the spectral density of the electrons in Dirac point is zero. Therefore the maximal probability of the light absorption will be at some smaller energy $\epsilon(p') < E_1 - E_0 = \Delta_{\mathrm{SAS}}$ with a larger density of states.

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