Scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR (31 October 1990)

Usp. Fiz. Nauk **161**, 163–171 (March 1991)

A scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR was held on 31 October 1990 at the S. I. Vavilov Institute of Physics Problems of the Academy of Sciences of the USSR. The papers listed below were presented at this session:

1. I. V. Kukushkin and V. B. Timofeev. Magnetooptics of two-dimensional electrons in the ultraquantum limit.

2. V. S. Édelman. Development of scanning tunneling microscopy.

A brief summary of the papers is presented below.

I. V. Kukushkin and V. B. Timofeev. *Magnetooptics of two-dimensional electrons in the ultraquantum limit.* In the physics of low-dimensional systems, the center of attraction remains the problem of the ground state of interacting two-dimensional (2-D) electrons. The behavior of a 2-D electronic system as its density varies can be described by comparing the correlation energy $\langle V\rangle \approx e^2/\varepsilon a$, which leads to ordering of the electrons, with the kinetic energy $\langle K\rangle$, which delocalizes the particles (here $a=(\pi n_s)^{-1/2}$ is the interparticle distance, n_s is the surface density of electrons, and ε is the permittivity).[1] When there is a strong inequality $\langle V\rangle \gg \langle K\rangle$ long-range order can arise in the system of electrons and crystallization can ensue. This effect in the quantum limit was predicted by Wigner[2] more than 50 years ago.

In the absence of a magnetic field one distinguishes between the classical and quantum regimes in which the crystallization of 2-D electrons can set in. The classical case (or the limit of low densities) is bounded by the inequalities $\hbar^2/m^*a^2 \ll kT \ll e^2/\varepsilon a$ (m^* is the effective mass of the electrons). In this regime a phase transition from electron liquid to crystal occurs when the ratio $\langle V\rangle/\langle K\rangle = e^2(\pi n_s)^{1/2}/\varepsilon kT > \Gamma \approx 127$. Such a classical crystallization of 2-D electrons has been found and studied in experiments with electrons on the surface of helium.[3] As a result of these studies, the phase boundary of the transition was determined in the coordinates (n_s, T_c); the classical melting point $T_c = e^2(\pi n_s)^{1/2}/\Gamma_m \varepsilon k$ and the magnitude of the parameter Γ_m were found.

The quantum regime (or high-density limit) is realized under conditions in which $kT \ll \hbar^2/m^*a^2 \ll e^2/\varepsilon a$. In this region the ratio $\langle V\rangle/\langle K\rangle$ is sought as a function of the dimensionless parameter $r_s \equiv a/a_B$, where $a_B = \varepsilon\hbar/m^*e^2$ is the Bohr radius. Since the correlation energy is $\langle V\rangle \sim n_s^{1/2}$, while the kinetic energy is $\langle K\rangle \sim n_s$, the Wigner crystal proves stable if $r_s > r_W$, i.e., when the density of electrons does not exceed a certain limiting value $n_s \leqslant n_W = (r_W^2 \pi a_B^2)^{-1}$. Thus in this regime the phase diagram has a definite ending point on the concentration scale. Numerical calculations yield $r_W \approx 33$.[4] If one uses this value for r_W, then a quantum regime for crystallization for 2-D electrons on the surface of He can be expected at densities $n_W \approx 10^{13}$ cm^{-2}, while for 2-D electrons at an AlGaAs/GaAs heterojunction it can be expected at $n_W \approx 3\times 10^8$ cm^{-2}. In both cases one cannot experimentally realize the stated concentrations for fundamental reasons. Therefore, up to now Wigner crystallization of 2-D electrons in a quantum regime in the absence of a magnetic field has not been observed.

The behavior is very interesting of 2-D electrons in a strong transverse magnetic field. The magnetic field splits the continuum of electron energies into the discrete set of Landau levels $(N+1/2)\hbar\omega_c$ ($\omega_c = eH/m^*c$; N integer). The electrons lose their former degrees of freedom, and their motion acquires a finite character in cyclotron orbits with dimensions $(2N+1)^{1/2}l_0$ ($l_0 = (\hbar c/(eH))^{1/2}$ is the magnetic length). In the ultraquantum limit, in which the electrons occupy only the lowest Landau level, the kinetic energy substantially declines and practically coincides with the thermal energy of the "centers of gravity" of the electron orbits. Thus a strong magnetic field creates favorable conditions for spatial ordering of electrons and stimulates Wigner crystallization.

The degree of degeneracy of the Landau levels (or the capacity of the quantum states) n_0 is determined by the magnetic length $n_0 = 1/2\pi l_0^2$, while their occupancy by electrons is usually characterized by the occupancy factor $\nu = 2(l_0/a)^2 = n_s/n_0$. In the region of weak magnetic fields the Coulomb correlations do not play a decisive role. In the region ($\nu > 1$) the integral quantum Hall effect (QHE) is found,[5] which by its nature is a one-electron phenomenon.[6] As the magnetic field increases, the degeneracy of the quantum states increases, and the role of Coulomb correlations becomes ever more marked. Precisely when $\nu < 1$ the fractional QHE is observed,[7] which has no direct relationship to Wigner crystallization. This phenomenon involves the appearance of strongly correlated electronic states, which have been termed incompressible Fermi liquids (IFLs).[8] These states, sometimes also called Laughlin states, arise for fractional occupancies $\nu = 1/q$ (q is integral and odd owing to the symmetry properties of the multiparticle wave function). In magnetotransport experiments these states have been observed down to $\nu = 1/7$.[9]

At the same time, the known numerical calculations show that a Wigner crystal is stable for occupancies of quantum states beginning at some critical values $\nu = \nu_c = 1/3$ to $1/10$.[10] In this regard experimental studies of 2-D electronic

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systems in the ultraquantum limit become especially acute: $\nu \ll 1$; $kT \ll e^2/\varepsilon a \ll \hbar^2/ma^2$, $\hbar\omega_c$. Only experiment can answer the questions: when does crystallization of electrons stimulated by a magnetic field set in, and how does the liquid-to-crystal phase diagram look in the ultraquantum limit? The efforts of recent years have involved attempts to advance into this extremely interesting area–strong magnetic fields, sufficiently low temperatures, and relatively low concentrations.

The most widespread instrument for studying such systems is magnetotransport. However, as we progress into the region $\nu \ll 1$ and very low T, this method faces insuperable difficulties owing to the enhanced effects of strong localization. Recently an interesting method of radiofrequency absorption spectroscopy was proposed in this field.[11] By using this technique the first attempts were made to determine the low-frequency collective excitations in a correlated system of electrons, and also to seek the critical parameters (occupancy factor, temperature) associated with the crystallization of electrons.

To study an interacting system of 2-D electrons placed in a strong transverse magnetic field, we have proposed and developed another experimental method. Within the framework of this method, which is based on the methods of optical spectroscopy, one studies the radiative recombination of 2-D electrons with photoexcited holes localized in a monolayer of acceptors. Previously this optical method was successfully realized in regimes of the integral and fractional QHE in the case of a 2-D electron channel in metal-dielectric-semiconductor (MDS) silicon structures.[12] For magnetooptics in the quantum regime it proved more effective to use GaAs/AlGaAs heterostructures (HSs), in which a 2-D electron channel near a single heterojunction is spatially separated with a monolayer of acceptors (δ-doped HS).[13] In these HSs great mobilities of 2-D electrons are attained ($\sim 10^6$–10^7 cm^2/V·s), while the optical selection rules allow radiative recombination of electrons from the lowest spin state (i.e., the region of occupancy factors $\nu < 1$ is optically allowed). By measuring the spectral position of the luminescence line upon varying H, it was found that, in the range $1 < \nu < 2$, one observes a deviation of the $E_N(H)$ relationship (N is the principal quantum number) from linear. This deviation involves an increase in the exchange interaction of the electrons (this is the *effect of amplification of the g-factor*). With further increase in H and at sufficiently low T one observes additional jumpwise changes in the spectral position of the emission line, which occur in a narrow region of H near the fractional values $\nu = 2/3$, 1/3, 4/5, 3/5, 2/5, 1/5, 1/7, and 1/9.[14] The jumps in $\Delta E(H)$ are small in comparison with $\hbar\omega_c$ and disappear with increasing temperature. Figure 1 shows them on an enlarged scale as measured on different structures with respect to the linear dependence $E_0(H) = E_g + 1/(2\hbar\omega_c)$ as obtained in weak magnetic fields and then extrapolated toward large H. The jumpwise behavior that is found of the spectral position of the emission line at fractional ν is associated with jumps in the chemical potential in the system of 2-D electrons as they condense to an incompressible Fermi liquid. The amplitude of the jump equals the discontinuity in the chemical potential ξ; according to the IFL theory, the magnitude of $\Delta\xi$ for $\nu = 1/q$ is directly related to the Coulomb gap Δ_C, namely, $\Delta\xi = q\Delta_C$. The physical meaning consists in the idea that a change in

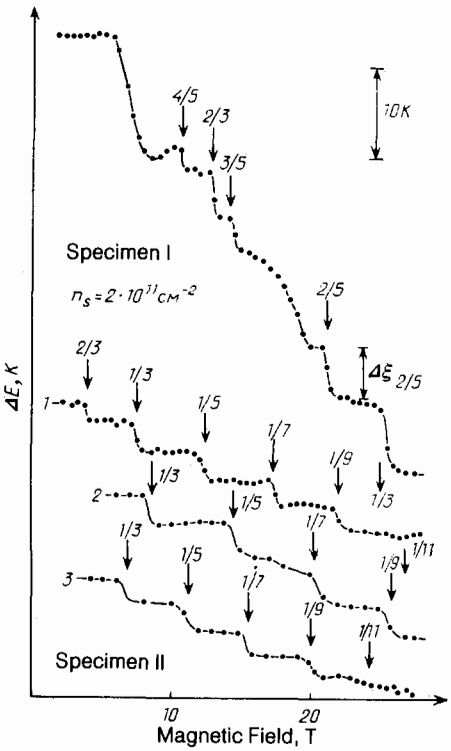

FIG. 1. Jumps in the spectral position of the luminescence line corresponding to recombination of electrons from the lower spin state with photoexcited holes in a δ-doped monolayer as measured upon varying the magnetic field in the specimens *1* and *2* at different concentrations: *1*–0.59×10^{11} cm^{-2}; *2*–0.7×10^{11} cm^{-2}; *3*–0.54×10^{11} cm^{-2}.

the number of electrons by unity is accompanied by creation (or absorption) of q-quasiparticle excitations having the fractional charge $e^* = e/q$, whose energy is separated from the ground state of the IFL by the gap Δ_C. The behavior that is found of $E_0(H)$ completely corresponds to that which we have observed in Si-MDS structures and confirms the interpretation according to which the jumps in $E_0(H)$ near $\nu = 1/q$ involve the creation (for $\nu < 1/q$) or absorption ($\nu > 1/q$) of excitations upon decrease in the number of 2-D electrons by unity upon radiative recombination with a hole. Thus, by using the above spectroscopic method it has been possible for the first time to observe an IFL state corresponding to $q = 1/9$, and also to measure the entire hierarchy of Coulomb gaps. Besides this, it has been shown experimentally that the jump in the chemical potential $\Delta\xi$ measurable in the optics under conditions of condensation to an IFL involves the activation energy $W(1/q)$ measured in magnetotransport by the simple relationship $\Delta\xi(1/q) = 2qW(1/q)$. This observation serves as an indirect proof that quasiparticle excitations have a fractional charge. Finally, the magnetooptical experiments have enabled tracing the behavior of the fractional QHE under conditions of disorder involving the fluctuations of a random potential.

Now we shall take up the spectroscopic observations of Wigner crystallization of two-dimensional electrons in a strong transverse magnetic field. These observations involve the study of the behavior of the radiative-recombination spectra of 2-D electrons in the heterojunction GaAs/AlGaAs in the ultraquantum limit.[15] In the spectra (Fig. 2), in addition to the fundamental line I_1 previously known,

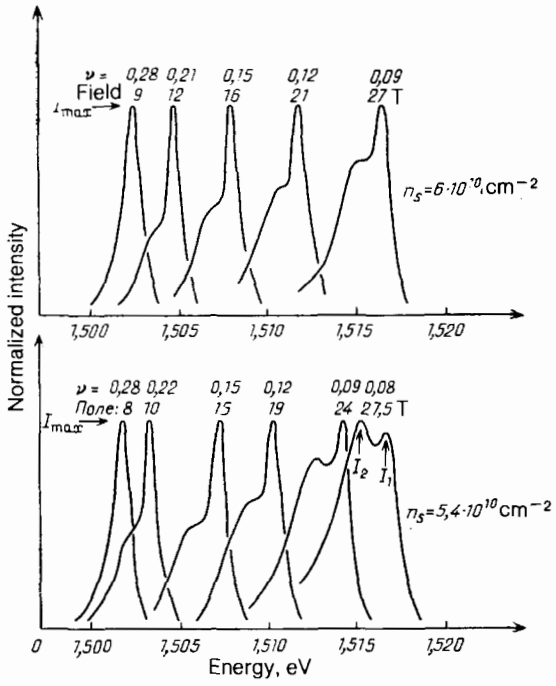

FIG. 2. Luminescence spectra measured at $T = 0.4$ K in different magnetic fields and at different concentrations.

which corresponds to recombination of electrons from the lower spin state, a new line appears, namely I_2, when certain values of the magnetic field are reached. This line increases with increasing H and dominates the spectrum at occupancy factors $\nu \approx 0.1$. It is shifted toward lower energies so that the splitting between the I_1 and I_2 lines amounts to about 1.4 meV. Simultaneously with the appearance of the I_2 line, the integral intensity of the luminescence in this region of the spectrum begins to decline strongly. The decline in the integral intensity of luminescence and the brightening of the I_2 line set in at the same value of the magnetic field H_k. It was shown that, in specimens with different concentrations n_s, H_k increases linearly with increasing n_s. Thus the phenomena that we have described do not depend on n_s and are observed starting at some critical value of the occupancy factor $\nu < \nu_{cr} = 0.28$. The I_2 line is very sensitive to temperature. At temperatures above the critical this line disappears from the spectrum (e.g., at $H = 26$ T we have $T_{cr} = 1.4$ K). Simultaneously with this, the integral intensity of luminescence increases and returns to the initial values measured at $H < H_k$. The critical temperature depends strongly on the occupancy factor: in the region $\nu < \nu_{cr}$ it increases with decreasing ν; however, for fractional $\nu = 1/5$, 1/7, and 1/9, where the ground state is an IFL, T_{cr} sharply declines.

The appearance of the new line I_2 in the spectra when $\nu < \nu_{cr} = 0.28$ is associated with the phenomenon of crystallization in the system of interacting electrons. In this interpretation the I_2 and I_1 lines correspond to the radiative recombination of 2-D electrons from the crystalline and liquid phases, respectively (when $\nu = 1/5$, 1/7, or 1/9 the Fermi liquid is incompressible). The shift of the I_2 line toward lower energies with respect to I_1 means that the ground state of the crystalline phase is the lowest. The threshold decrease in the signal of integral luminescence is a consequence of the strong localization of the electrons under crystallization conditions. The localization of electrons in this case has its own origin and involves the appearance of the crystal (polycrystal), which is pinned by the inhomogeneities of the random potential. Upon increase in the temperature above the critical value, when the crystal is melted and the electrons are delocalized, the signal of the integral intensity increases and ceases to depend on the magnitude of the magnetic field.

The phase diagram of the liquid-to-crystal transition proves very interesting. According to the known theoretical concepts, the line of phase equilibrium in the ν-T plane begins at $\nu \leqslant \nu_{cr}$ and behaves monotonically. According to our observations (Fig. 3) the liquid-to-crystal phase diagram is dissected by gaps at $\nu = 1/5$, 1/7, and 1/9, where the IFL proves more stable.

It seems to us that the most interesting lines of study in this field in the near future will involve studying the liquid-to-crystal phase diagram in the coordinates (n_s, T, H) and the spectrum itself of the collective excitations of the electronic crystalline phase.

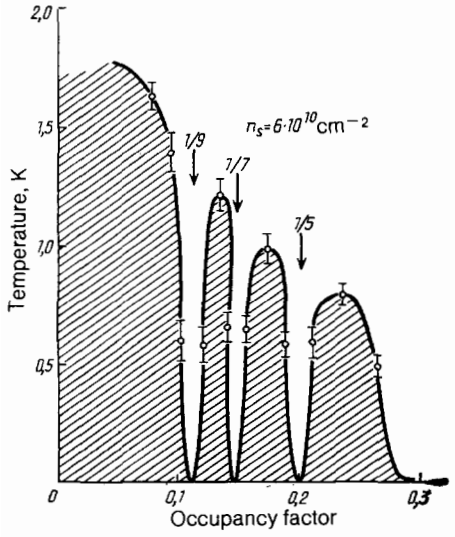

FIG. 3. Phase diagram of the liquid-Wigner crystal transition.

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