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CONFERENCES AND SYMPOSIA

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Mesoscopic and strongly correlated electron systems "Chernogolovka 97"

2. The quantum Hall effect and noise in mesoscopic systems

The second session of the conference included the following presentations:

(1) **Ashoori R C** (Massachusetts Institute of Technology, Cambridge, USA) "Subsurface electronic structure microscopy of the quantum Hall effect";

(2) **Eisenstein J** (California Institute of Technology, USA) "Coulomb drag and tunneling between 2D electron gases at high magnetic field";

(3) **Dorozhkin S I, Dorokhova M O** (Institute of Solid State Physics, RAS, Chernogolovka, Russia), **Haug R J** (Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany), **Ploog K** (Paul-Drude Institut für Festkörperelektronik, Berlin, Germany) "Capacitance spectroscopy of the fractional quantum Hall effect";

(4) **Goldberg B** (Boston University, USA) "Optical measurements of skyrmions in a quantum Hall ferromagnet";

(5) **Kukushkin I V** (Institute of Solid State Physics, RAS, Chernogolovka, Russia; Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany), **von Klitzing K, Eberl K** (Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany) "Spin polarization of two-dimensional electron system. Experimental test of the skyrmion theory";

(6) **Iordanskiĭ S V** (Landau Institute for Theoretical Physics, RAS, Chernogolovka, Russia) "Non-singular vortex-skyrmions in a two-dimensional electron system";

(7) **Apel W** (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany), **Bychkov Yu A** (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, Landau Institute for Theoretical Physics, RAS, Chernogolovka, Russia) "Microscopic derivation of the effective Lagrangian for skyrmions in an interacting two-dimensional electron gas at small g-factor";

(8) **Dolgopolov V T, Shashkin A A, Aristov A V** (Institute of Solid State Physics, RAS, Chernogolovka, Russia), **Schmerek D, Hansen W** (Institut für Angewandte Physik, Universität Hamburg, Germany), **Kotthaus J P** (Ludwig-Maximilians-Universität, München, Germany), **Holland M** (University of Glasgow, United Kingdom) "Nonlinear screening, and spin and cyclotron gaps in the 2D electron gas of GaAs/AlGaAs heterojunctions";

(9) **Nazarov Yu V , Khaetskiĭ A V** (Delft University of Technology, The Netherlands) "Quantum phase transition in a skyrmion lattice";

(10) **Maude D K** (High Magnetic Field Laboratory, Grenoble, France) et al. "Spin texture excitations in a two-dimensional electron gas under hydrostatic pressure";

(11) **Levitov L S, Shytov A V** (Massachusetts Institute of Technology, Cambridge, USA), **Halperin B I** (Harvard University, Cambridge, USA) "Effective action and Green's function for a compressible QH state edge";

(12) **Rashba E** (University of Utah, USA) "Anyon excitons, composite fermions and exclusion statistics";

(13) **Glattli D C, Saminadayar L** (Service de Physique de l'Etat Condensé, Saclay, France), **Jin Y, Etienne B** (Laboratoire de Microelectronique et Microstructures, CNRS, Bagneux, France) "Shot noise in mesoscopic systems and in the quantum Hall regime: detection of $e/3$ quasiparticles";

(14) **Lesovik G B** (Landau Institute for Theoretical Physics, RAS, Chernogolovka, Russia) "Recording zero-point current and voltage fluctuations";

(15) **Blanter Ya M, Büttiker M** (Geneva University, Switzerland), **van Langen S A** (Institut-Lorentz, Leiden University, The Netherlands) "Exchange effects in shot noise in multi-terminal devices".

Papers 3, 6, 7, 8, 11, 14, and 15 are published below. For papers 2, 9, and 13 see publications and e-prints: *Phys. Rev. Lett.* **80** 1714 (1998), cond-mat/9710041; *Phys. Rev. Lett.* **80** 576 (1998), cond-mat/9703159 and cond-mat/9706307, respectively.

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Capacitance spectroscopy of the fractional quantum Hall effect

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R J Haug, K Ploog

It is well known that the fractional quantum Hall effect (FQHE) arises as a result of the condensation of a two-dimensional electron system (2DES) into a correlated liquid state (a Laughlin liquid [1, 2]), separated from the neighboring excited states by an energy gap. The condensation takes place at some fractional values $\nu_f = p/q$ of the filling factor of Landau levels $\nu = n_s/(eH/hc)$. Here n_s is the surface electron concentration, eH/hc is the degeneracy of the Landau level in the magnetic field, and H, p, and q are integers (q is usually odd). In the vicinity of these filling factors the system is described as a combination of a Laughlin liquid and some quasiparticles with fractional charge $e^* = e/q$ whose density n_q is determined from the condition of the changed charge of the 2DES

$$n_q = \frac{e}{e^*}\,\frac{eH}{hc}\,|\nu - \nu_f|\,.$$

As a result, a singular term $\Delta^{\pm} n_q$ appears in the density of the 2DES energy $E(n_s)$, which corresponds to the occurrence of quasi-electron excitations at $\nu > \nu_f$ and quasi-hole excitations at $\nu < \nu_f$ with energies Δ^+ and Δ^-, respectively. The chemical potential of the 2DES $\mu = \mathrm{d}E/\mathrm{d}n_s$ has a jump at $\nu = \nu_f$ equal to

$$\delta\mu = \frac{e}{e^*}\,(\Delta^+ + \Delta^-)\,.$$

As the filling factor deviates considerably from ν_f the description in terms of noninteracting quasiparticles does not seem to be adequate. Besides, as $|\nu - \nu_f|$ increases the 2DES system can transfer to another (non-correlated) state when its energy happens to be lower than the energy of the excited Laughlin state. A schematic representation of the dependence $E(n_s)$ is given in the inset to Fig. 1. For the FQHE the charge is transferred both by the Laughlin liquid (non-dissipative Hall current), and by thermally activated quasiparticles. The latter process is attended by dissipation. When the quasiparticles are few in number and their levels broaden insignificantly, the activation energy of dissipative conductivity is $E_a = (\Delta^+ + \Delta^-)/2$. Note that a consistent theory taking into account the influence of disorder in the 2DES on the FQHE is still lacking. Following the authors of Refs [3, 4], we can assume that long-period (as compared to average distance between electrons) fluctuations of the potential lead to heterogeneous broadening of the singularity $E(n_s)$, while short-period ones decrease the gap value in the quasiparticle spectrum.

In this paper we review the recent results of Refs [5, 6], where the fractional quantum Hall effect at filling factors $\nu = 1/3$ and $2/3$ was studied by the methods of capacitance spectroscopy and magnetotransport and analyze the key assumptions underlying these methods. Capacitance spectroscopy enables one to study the thermodynamic properties of the ground state of a 2DES providing the data on the second derivative

$$\frac{\mathrm{d}^2E}{\mathrm{d}n_s^2} = \frac{\mathrm{d}\mu}{\mathrm{d}n_s}\,.$$

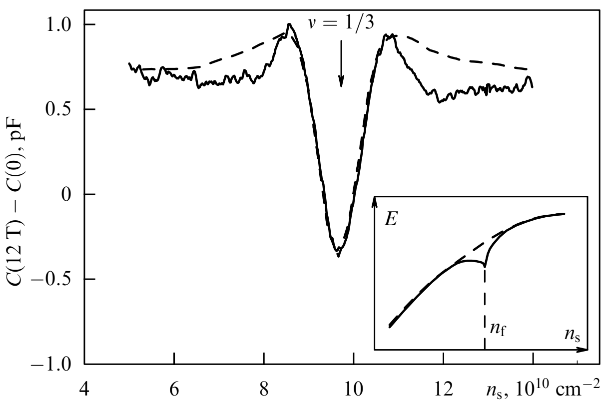

Figure 1. Dependence of the difference of capacitances in fields $H = 12$ T and $H = 0$ on the electron concentration (solid line). The dashed line corresponds to expression (3) with fitting parameters $F = 0.3$ and $\sigma = 4.2 \times 10^9$ cm^{-2}. To improve the agreement between the theoretical and experimental data, the theoretical curve is shifted in the vertical direction. The inset shows schematically the dependence of the 2DES energy density E on n_s for the FQHE (solid line) and without it (dashed line).

This quantity affects the measured capacitance C of a parallel-plate capacitor formed from the 2DES and a parallel metal film (gate) due to the potential difference between them [7]:

$$\frac{1}{C} = \frac{1}{C_g} - \frac{1}{Ge^2}\frac{\mathrm{d}\mu}{\mathrm{d}n_s} = \frac{1}{C_g} - \frac{1}{Ge^2}\frac{\mathrm{d}^2E}{\mathrm{d}n_s^2}\,, \tag{1}$$

Here G is the area of the 2DES under the gate, and $C_g = \kappa G/4\pi d$ is the geometrical capacitance of the capacitor, determined by the effective distance between the 2DES and the gate $d = d_0 + z_0(n_s) + n_s\,\mathrm{d}z_0/\mathrm{d}n_s$ [8]. Here d_0 is the distance between the gate and GaAs/AlGaAs heterojunction, and z_0 is the distance between the heterojunction and the 'center of gravity' of the squared electron wave function (for an ideally two-dimensional system $z_0 = 0$). In the case of long-period fluctuations of electron density in the sample, formula (1) will include averaged values of E and n_s.

We studied experimentally the 2DES with electron mobility of the order of 1×10^6 cm^2(V $\cdot$ s)$^{-1}$, arising in GaAs/AlGaAs gated heterostructures. The electron concentration n_s was varied by applying a constant voltage between the gate and the 2DES. The samples had the shape of Hall junctions with ohmic voltage and current contacts at the 2DES to measure the Hall resistance and magnetoresistance. The capacitance between these contacts and the gate was measured by applying an alternating voltage of frequency 9.2 Hz. In this experimental design the measurement of capacitance becomes almost impracticable at very small values of the diagonal conductivity σ_{xx} of the 2DES [9], therefore we had to use not very strong magnetic fields and not extremely low temperatures. Actually, in measuring the capacitance we consistently verified the lack of the current component through it, which was in phase with the applied alternating voltage. Thus we avoided the effect of 2DES resistance on the experimental data. There are two ways to extend the applications of the method by decreasing the resistance effects. Firstly, one can use samples with the tunneling contact distributed over the 2DES [10]. Secondly, the technique of a 'non-fixed gate' can be applied [11]. However, as far as we know, the latter variant has only been used to study the integer quantum Hall effect.

According to formula (1), in an ideal system the chemical potential jumps at fractional filling factors must lead to δ-like singularities in the dependencies $C(n_s)$. However the experiment (see Fig.1) demonstrates only a minor singularity in the capacitance (the minimum at the fractional filling factor and two maxima on each side). The minimum on the capacitance curve corresponds to the knee in the dependence $E(n_s)$ at $\nu_f = 1/3$, and the two side maxima correspond to the minima $\mathrm{d}^2E/\mathrm{d}n_s^2$, which must arise if upon the appearance of the 2DES state the dependence $E(n_s)$ changes only within the narrow concentration range near the fractional ν_f as is shown in the inset to Fig. 1. The observed broadening of the capacitance singularity was found to be independent of the magnetic field and temperature and similar for the capacitance singularities observed at both fractional and integer filling factors, the ratio $\delta\mu/T$ changing by an order of magnitude. Besides, the distance between the two maxima of the capacitance $\delta n_s \approx 2.2 \times 10^{10}$ cm^{-2} remained virtually constant upon variation of the magnetic field from 6 to 12 T. These results suggest that the factor responsible for the broadening are the fluctuations of the carrier concentration in the sample.

If δn_s had exceeded greatly the concentration dispersion σ, the analysis of the capacitance dependencies would have allowed us to determine directly the dispersion σ and the chemical potential jump $\delta\mu$. However under the conditions of our experiment this ratio is not fulfilled so that quantitative processing of the experimental results requires data on the dependence $E(n_s)$ in the range $n_f - \sigma < n_s < n_f + \sigma$. An approach to quantitative processing of capacitance results in this situation was suggested in Refs [3, 4], where the deviation from linear parts on the dependence $E(n_s)$ near the FQHE state was described in terms of interacting quasiparticles with charge e^*, arranged in a regular array and neutralized by a uniformly distributed background charge. The main terms in the total energy of the uniform system, leading to the singularity in $\mathrm{d}^2E/\mathrm{d}n_s^2$, take the form [3, 4]:

$$E_{\mathrm{fr}}(n_s) = \frac{\delta\mu|n_s - n_f|}{2} - \frac{\sqrt{2\pi}\,\beta}{\kappa}\sqrt{\frac{e^*}{e}}\,e^2|n_s - n_f|^{3/2}\,. \qquad (2)$$

Here $\beta \approx 0.78$ is the constant weakly depending on the lattice type, and n_f is the concentration corresponding to the fractional filling factor. The concentration distribution in the sample is considered to be Gaussian [3] with a dispersion σ. As is known, for the ideal DES the theoretical value of the chemical potential jump at $\nu_f = 1/3$, being equal to $\delta\mu_{\mathrm{th}} \simeq 0.3e^2/\kappa l$ [12] (where $l = (\hbar c/eH)^{1/2}$ is the magnetic length), greatly exceeds the experimental values. This suggests that the short-period fluctuations of the potential in the sample change the correlation energy caused by the condensation of the electron system into the Laughlin liquid state. It was proposed in Ref. [4] to take this effect into account phenomenologically by introducing the factor $F < 1$ into (2). Non-uniform broadening of singularities in capacitance is allowed for in Refs [3, 4] by inserting the Gaussian distribution of the electron concentration with dispersion σ. Averaging of the second derivative $\mathrm{d}^2E_{\mathrm{fr}}/\mathrm{d}n_s^2$ with respect to concentration n_s yields the following expression for the dependence of the singularity on the capacitance curve δC on the average concentration n_s:

$$\frac{\delta C}{C^2} = \frac{1}{Ge^2}\frac{\mathrm{d}\mu}{\mathrm{d}n_s} = \frac{1}{Ge^2}\left[F\,\frac{\delta\mu_{\mathrm{th}}}{\sqrt{2\pi}\,\sigma}\exp(-z^2) - F\,\frac{3\beta}{4}\,\frac{e^2}{\sqrt{q}\,\kappa}\left(\frac{2}{\sigma^2}\right)^{1/4}\int_{-\infty}^{\infty}\frac{\exp(-t^2)}{\sqrt{|t+z|}}\,\mathrm{d}t\right]. \qquad (3)$$

Here $z = (n_s - n_f)/\sqrt{2}\sigma$, and $\kappa = 13$ is the dielectric constant in GaAs. This expression includes two fitting parameters F and σ. Calculating them by comparison of (3) with the experimental results (see Fig. 1), we can find the experimental chemical potential jump $\delta\mu = F\delta\mu_{\mathrm{th}}$. These data are presented in Fig. 2 for different magnetic fields. The independence of the singularity width from the magnetic field discussed above implies the independence of the value of $\sigma = 4.2 \times 10^9$ cm^{-2} from the field H (to the limit of experimental error estimated at 10%).

The most widely used method to determine the energy gap in the quasiparticle spectrum for the FQHE, is the measurement of the activation energy E_a for the dissipative conductivity σ_{xx} or magnetoresistance R_{xx} (Fig. 3). The measurements combined with the measurement of the chemical potential jump allow one to check the experimentally predicted fractional charge of quasiparticles by the ratio

$$\frac{E_a}{\delta\mu} = \frac{1}{2}\,\frac{e^*}{e}\,.$$

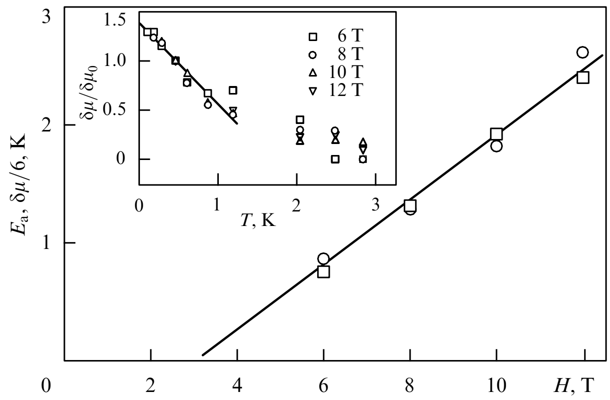

Figure 2. Comparison of $\delta\mu/6$ (circles) and E_a (squares) measured at various magnetic fields; $\delta\mu$ is measured at $T = 0.5$ K. The inset shows the temperature dependence of the chemical potential jump, which is normalized with respect to its value at $T = 0.5$ K taken from Ref. [14].

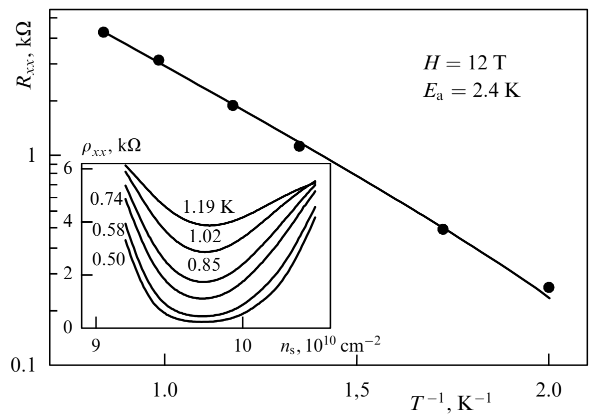

Figure 3. Temperature dependence of magnetoresistance measured at the minimum at $\nu_f = 1/3$ (circles) for a magnetic field $H = 12$ T. The solid line corresponds to the activation energy $E_a = 2.4$ K. The inset plots the dependencies $R_{xx}(n_s)$ measured at various temperatures indicated on the curves.

The results of such a check are shown in Fig. 2. The average ratio $\delta\mu/E_a$ for four values of the magnetic field H is 6.2; the latter agrees with the theoretically predicted quasiparticle charge $e^* = e/3$ at the filling factor $1/3$.

A significant aspect of all the energy gap measurements for the FQHE is the temperature dependence of the gaps [13, 14], which, in particular, poses the question of the reliability of the gap values calculated by the activation energy data. The temperature dependence of the chemical potential jump at the filling factor $1/3$ was investigated in Ref. [14], where at $0.15\ \mathrm{K} < T < 1.5$ K the linear temperature dependence of the minimum capacitance was observed (see, the inset in Fig. 2). When the activation energy measurements are carried out over the temperature interval, where the energy gap $\Delta = \Delta^+ + \Delta^-$ depends linearly on temperature, i.e. $\Delta = \Delta_0 - \alpha T$, then the dependence of dissipative conductivity is expected to be activated with an activation energy of $E_a = \Delta_0/2$.

Based on the capacitance spectroscopy method, we have developed a method to investigate the 2DES spin polarization, which can be used over a wide range of filling factors. The method was used to study the 2DES spin polarization at filling factors $\nu < 1$. According to numerical calculations [15, 16] in the case of systems with a small number of particles, for the studied magnetic fields the ratio between the Zeeman and Coulomb energies for the 2DES based on GaAs/AlGaAs heterojunction is such that their polarization at $\nu < 1$ can differ from the complete polarization of the system even in the ground state. The increase in the Zeeman energy with respect to the case of complete polarization is compensated by the decrease in the energy of electron-electron interactions. The method involves the measurement of small changes in capacitance ΔC, caused by adding a magnetic field H_p parallel to the 2DES (i.e., the total magnetic field is tilted with respect to the 2DES plane). In an ideal two dimensional system with no spin-orbit interaction the applied field H_p directly affects only the Zeeman energy $E_Z = g\mu_B H S_z$, where S_z is the projection of the total spin S on the magnetic field direction (both the values are given per unit square of 2DES), and g is the Lande factor equal to 0.44 in GaAs. In the ground state the projection is $S_z = -S$. Assuming the spin of the system to be independent of H_p, we have for ΔC:

$$\Delta C(n_s, H_n, H_p) \equiv C(n_s, H_n, H_p) - C(n_s, H_n, 0) \approx -\frac{C^2}{e^2 G}\, g\mu_B (H - H_n) \frac{d^2 S_z}{dn_s^2}\,, \qquad (4)$$

where H_n is the magnetic field component perpendicular to the 2DES and $\Delta C \ll C$. Therefore, changes in the capacitance characterize the spin polarization of the system. The assumption of the independence of the spin and the energy of the electron–electron interaction on H_p is used in virtually all the experiments (see, for example, Refs [17–19]), where the 2DES spin polarization is investigated from changes in the corresponding energy gap upon adding H_p. The validity of this assumption is demonstrated, for example, by the results of numerical calculations, which show that the spin of a partly polarized system may not change with a considerable change (by 3 times in Fig. 4 of Ref. [16]) of Zeeman energy. Our data in favor of this assumption will be given below.

Figure 4 shows the dependence of the capacitance on n_s for various values of the total magnetic field H and fixed $H_n = 8$ T. The parallel component H_p mainly results in changes of the capacitance curves at $\nu \gtrsim 2/3$. First, let us discuss another effect involving a virtually parallel vertical shift of the curves (not plotted in Fig. 4). The shift increases as H_p rises and is approximately equal to 0.1 pF at $H = 12$ T and $H_n = 6$ T. It is independent of temperature and determined for each curve on the basis of similar measurements at $T = 4.2$ K, when the FQHE does not exist. The temperature-independent shift demonstrates that it is not due to the Zeeman energy caused by the tilted magnetic field, and hence not described by (4). Actually, since the typical Zeeman splitting in the studied range of fields is about ~ 2 K, the value of S_z would decrease substantially for a temperature increase to 4.2 K [16], changing d^2S_z/d^2n_s. Apart from this, the explanation of the shift by the change in the Zeeman energy contradicts commonly accepted notions [16, 20] on the complete polarization of the 2DES ground state at $\nu = 1/3$, since in this case the capacitance increase near $\nu > 1/3$ means

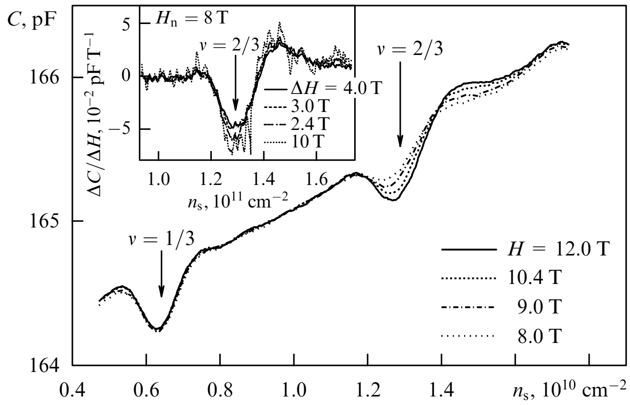

Figure 4. Dependence of the capacitance C on the concentration n_s for various H_p and fixed $H_n = 8$ T. The positions of filling factors $\nu = 1/3$ and 2/3 are indicated by arrows, $T = 0.5$ K. The inset plots the differences $\Delta C = C(H) - C(H_n)$ normalized with respect to $\Delta H = H - H_n$.

a further increase in the 2DES polarization. (Under the conditions of the experiment the magnitude $g\mu_B H \gg T$ which suggests that we are dealing with the spin polarization of the 2DES ground state.) The more probable origin of the capacitance shift is a modification of the electron wave function by the tilted field, resulting in a changed z_0, and hence a changed C_g (see also Refs [8, 21]).

Thus, we relate the capacitance changing in the tilted magnetic field (Fig. 4) to E_Z changing in accordance with (4). The obtained data allow us to determine the 2DES spin polarization over the whole studied interval of filling factors, using the commonly accepted concept of the complete polarization of the 2DES ground state at $\nu_f = 1/3$. Really in this case $S_z(1/3) = -n_s(1/3)/2$, while the unchanged capacitance at $\nu = 1/3$ means that $dS_z/dn_s(1/3) = -1/2$. Making the double integration of $C(H) - C(H_n)$ over n_s under these boundary conditions, we arrive at the dependencies S_z/S_z^{max} ($S_z^{max} = -n_s/2$) plotted in Fig. 5. Over the interval $0.3 < \nu < 0.6$ within the limits of experimental accuracy, $S_z(\nu)/S_z^{max} = 1$ and it is not depicted

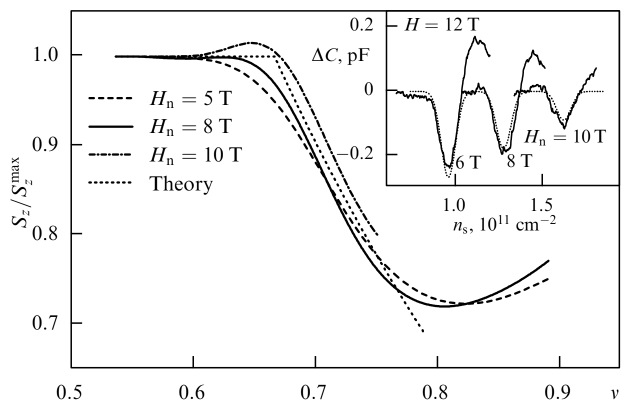

Figure 5. Dependence of the relative polarization S_z/S_z^{max} of the system on the filling factor ν, determined by measurements at $H_n = 6$, 8, 10 T and $H = 12$ T. The inset shows the changes in capacitance $\Delta C = C(12\ \mathrm{T}) - C(H_n)$ (solid lines) measured at various fields H_n; the field magnitude is indicated at the curves. The dashed line corresponds to the calculated data described in the paper.

in the figure. The 2DES remains completely polarized up to $\nu = 2/3$ (accounting for the concentration dispersion). Then electrons with spins inverted with respect to the field arise in the system, and the polarization decreases. For a further increase in ν the dependence $S_z/S_z^{\max}$ has a minimum at $\nu \sim 0.8$. Note that all the experimental curves in Fig. 5 virtually correspond to the universal dependence $S_z/S_z^{\max}$ on ν (accurate to the dispersion of the filling factor $\sigma/(eH_\mathrm{n}/hc)$, which is different for the curves measured at various fields H_n). The universal behavior of the spin polarization in the vicinity of $\nu = 2/3$ is demonstrated in the inset of the Fig. 5 by the comparison between the experimental dependencies of ΔC on n_s and the data calculated for the case when the system is completely polarized and $\mathrm{d}S_z/\mathrm{d}n_\mathrm{s} = -1/2$ in the absence of the concentration dispersion at $\nu \leqslant 2/3$, while at $\nu > 2/3$ all the electrons involved in the system have spins inverted with respect to the field, i.e. $\mathrm{d}S_z/\mathrm{d}n_\mathrm{s} = 1/2$. The calculated curves in the inset are obtained by the chemical potential jump changed by the tilted magnetic field and averaged over the Gaussian distribution with the dispersion earlier determined, $\sigma = 4.2 \times 10^9$ cm^{-2}. The dependence of $S_z/S_z^{\max}$ on ν, corresponding to the values of $\mathrm{d}S_z/\mathrm{d}n_\mathrm{s}$ used in the calculations, is shown by the dashed line in Fig. 5 for the system with zero dispersion. Note that the jump of the derivative $\mathrm{d}S_z/\mathrm{d}n_\mathrm{s}$ at $\nu = 2/3$ corresponds to the completely spin polarized state of the 2DES at this filling factor and the quasi-hole (or quasi-electron) excitations with spin coinciding (reverted) with the magnetic field, as was predicted in Ref. [15] by numerical calculations for systems of few particles.

The universal dependence $S_z/S_z^{\max}$ on ν, presented in Fig. 5, demonstrates that the assumption of the independence of the 2DES spin and the Zeeman energy, which was made to derive (4), is fulfilled under the conditions of our experiment. We show that this assumption actually results in the universal dependence $S_z/S_z^{\max}$ on ν and *vice versa*. If the Coulomb energy at fixed filling factors and relative polarization is proportional to $e^2 n_\mathrm{s}^{3/2}$ [1], then the spin-dependent part E_S of the total energy of the 2DES ground state can be written as

$$E_S = e^2 n_\mathrm{s}^{3/2} \phi\left(\nu, \frac{S_z}{n_\mathrm{s}}\right) - g\mu_\mathrm{B} H S_z \,.$$

Here ϕ is a function of the variables ν and S_z/n_s. The equilibrium value of S_z should be found by the condition $\partial E_S/\partial S_z = 0$. It is easily seen that the universal dependence of $S_z(\nu)/n_\mathrm{s}$ on ν results from the solution of the equation only when the Zeeman effect can be neglected and the spin value can be found from the equation $\partial\phi/\partial S_z = 0$. Additional experimental evidence in favor of the discussed assumption is the observation of the linear dependence of ΔC on $(H - H_\mathrm{n})$ predicted by Eqn (4) for large changes of the total field H. The corresponding data are shown in the inset of Fig. 4. The normalized values of $\Delta C/(H - H_\mathrm{n})$ actually correspond to the universal dependence within experimental error.

Thus, by capacitance spectroscopy, we have measured quasi-particle charge for the FQHE and the 2DES spin polarization. We have discussed the key assumptions and restrictions of the method.

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Non-singular vortex-skyrmions in a two-dimensional electron system

S V Iordanskiĭ

The problem of the states of a thermodynamical system of two-dimensional interacting electrons in a strong magnetic field is still not solved completely. Various qualitative and phenomenological results have been obtained and extensive experimental material has been accumulated.

Recently considerable attention has been focussed on the description of states at the Landau level with of filling factor of 1. This Landau level in a strong magnetic field can be considered in the Hartree – Fock approximation with the Slater determinant corresponding to a complete filling of the level. In this case the negative exchange energy causes ferromagnetic ordering of spins.

In a ferromagnet special macroscopic excitations may form corresponding to a slow rotation of the electron spin in space. This produces a topologically nontrivial mapping of a two-dimensional plane with long-range ferromagnetic ordering onto the sphere of average spin directions [1, 2]. Similar states were suggested for the two-dimensional electron gas in a strong magnetic field [3, 4].

Leaving aside phenomenological and numerical data, we will concentrate on the results obtained by a gradient expansion of the rotation matrix [5 – 7]. These papers use the approximation of wave functions projected onto a single Landau level.

Let us point out the main problems of this approach. The authors of Ref. [5 – 7] use an electron spin rotation matrix depending on two Euler angles. However in this case, one of the Euler angles must be written as

$$\alpha = m\varphi + \tilde{\alpha}(\varphi) \,, \qquad (1)$$

where $\tilde{\alpha}$ is a regular periodic function of the polar angle φ in a certain coordinate system, m coinciding with the mapping