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Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (27 April 1994)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on 27 April 1994 at the P L Kapitsa Institute of Physical Problems. The following papers were presented at this session:

(1) **V B Shikin** "Charges near the free surface of liquid helium: collective effect";

(2) **V M Pudalov** "From the quantum Hall effect to a Wigner crystal".

Summaries of these papers are given below.

PACS numbers: 01.10.Fv; 67.57.Np

Charges near the free surface of liquid helium: collective effects

V B Shikin

Two types of two-dimensional (2D) charged systems can appear near the free surface of liquid helium: surface electrons and surface ions [1]. The existence of these two systems has been predicted almost simultaneously (see Ref. [2]). However, the electron variant of the problem has subsequently been investigated more thoroughly both theoretically and experimentally. The interest in 2D ion systems has increased significantly only recently because of certain specific features of their collective behaviour.

This short review is intended to serve as a brief introduction to the current status of the problem of the 2D ion systems near the free surface of liquid helium. In addition, some qualitatively new trends in the study of the properties of 2D electron systems above helium are discussed.

2D ion system under the surface of helium

1. Charged particles near the surface of liquid helium on the liquid phase side are repelled from the surface by a force $\boldsymbol{F}$ of polarisation origin (image force)

$$F = \left(\frac{e}{2z}\right)^2 \frac{\varepsilon - 1}{\varepsilon(\varepsilon + 1)} \; ; \tag{1}$$

where e is the charge of the particle; ε is the dielectric constant (permittivity) of helium, which is 1 for vacuum; z is the actual distance of the ion from the free surface. The repulsion, i.e. the inequality $F > 0$, clearly applies to ions of either charge, since F defined by Eqn (1) contains the square of the charge.

Introduction of an additional electric field $\boldsymbol{E}_\perp$, which drives ions with a given sign to the surface of helium, makes it possible to balance out the action of the force F defined by Eqn (1) at a certain finite distance z_0 from the free surface [2]

$$z_0 = \frac{1}{2}\left[\frac{e(\varepsilon - 1)}{E_\perp \varepsilon(\varepsilon + 1)}\right]^{1/2} . \tag{2}$$

It follows that the competition between the image force (1) and the external field $\boldsymbol{E}_\perp$ localises ions with a given charge, introduced into liquid helium, in the $z = z_0$ plane transforming the ion system into a two-dimensional one.

Near the equilibrium position z_0 the ions may execute harmonic vibrations of frequency ω_i [2]

$$\omega_i^2 = \frac{1}{2M_i}\frac{e^2(\varepsilon - 1)}{z_0^3(\varepsilon + 1)}, \tag{3}$$

where M_i are the effective masses of ions with a given sign (cations or anions). Determination of this frequency gives direct information on the effective masses of helium ions. Such experiments have been carried out in France [3] and gave the following values:

$$M_+ = (45 \pm 2)m_4 , \quad M_- = (243 \pm 5)m_4 ; \tag{4}$$

where m_4 is the mass of the He^4 atom.

The results (4) are particularly clear for negative ions which are known to be hollow bubbles of radius R, containing an electron localised inside the bubble. The theoretical bubble radius is $R \approx 18$ A [1]. The corresponding effective mass is simply the associated hydrodynamic mass of a sphere of radius R in an ideal liquid. Hence the experimental value of M_- makes it possible to estimate the radius of the sphere:

$$R \approx 17.4 \text{ A} . \tag{5}$$

The agreement between the calculated and experimental values of R is very good.

2. The problem of the effective mass of helium ions near the surface of liquid helium has been studied further in connection with experiments on the excitation of plasma oscilla-tions. The results obtained [4] demonstrate that classical two-dimensional plasma oscillations (i.e. oscillations with the dispersion law $\omega \propto q^{1/2}$, where ω is the frequency and q is the corresponding wavenumber of the oscillations) occur in the 2D ion system, but the effective mass of positive ions is strongly temperature dependent. Fig. 1, taken from Ref. [4], demonstrates the strength of

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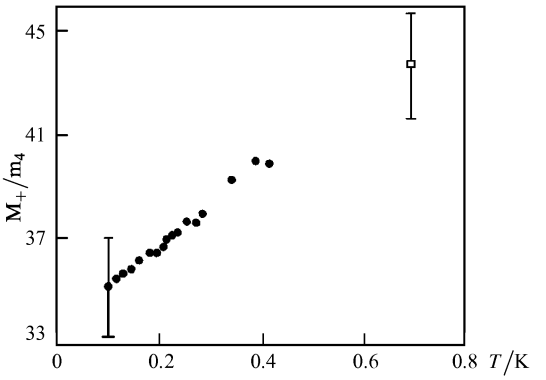

Figure 1. Temperature dependence of the effective mass of a cation M_+ near the surface of liquid helium [4].

this dependence. One therefore has to distinguish between two different masses: vertical and longitudinal, which have different numerical values. So far, this interesting observation has not been given a convincing explanation, but the existence of the effect has been confirmed by later independent measurements [5].

3. Investigations of the 2D ion systems have led, naturally, to the question of the Coulomb crystallisation of ions. This effect, predicted by Wigner over 50 years ago, has been discovered and investigated in detail for a 2D system of electrons above helium, as discussed several times in the present journal [6–8]. Nevertheless, the example of the 2D ion system is particularly interesting because in this case a theoretical description of the details of the ion–ripplon resonances, which appear in the course of the Coulomb crystallisation, is possible with the use of perturbation theory. Electrons above helium represent the other limiting case of strong coupling (in accordance with the classification of Monarkha [9]) and the simple perturbation theory does not work.

One of the characteristic features of the limiting case of weak coupling in the theory of ion–ripplon resonances, which accompany the Coulomb crystallisation, is the relative ease with which the nonlinear effects appear. Experiments [5] have confirmed this prediction. Fig. 2, taken from Ref. [5], demonstrates the excitation of the first of the ion-ripplon resonances which occurs around the frequency

$$\omega_1^2 = \frac{\alpha}{\rho} q_1^3, \qquad q_1 = \frac{2\pi}{a}; \tag{6}$$

here, ρ is the density of helium, α is its surface tension and a^{-2} is the average density of ions in the 2D system. In this figure we can also see nonlinear submultiple resonances at frequencies $\omega_1/2$ and $\omega_1/3$.

Naturally, the resonances are much less sharp than that those involving electrons. However, the phase diagram of melting of an ionic crystal, deduced from an analysis of the temperature dependence of the $\omega = \omega_1$ peak, has the necessary properties: the lattice is triangular, the law $T_c \propto a^{-1}$ is obeyed, and the coefficient of proportionality in this law

$$\Gamma = \frac{e^2(\pi n_s)^{1/2}}{T_c} = 130, \qquad n_s = a^{-2} \tag{7}$$

(where T_c is the melting point) is of the same order of magnitude as for an electronic crystal [1].

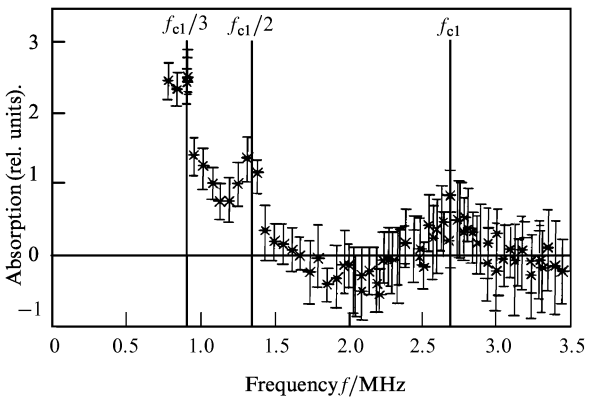

Figure 2. Detection of the Coulomb crystallisation, which manifests itself by the absorption of an rf field at a frequency $f_{c1} = \omega_1/2\pi$, where ω_1 is taken from Ref. [6]. The experiment was carried out on a system of 2D helium cations under the following conditions: $T = 10$ mK, $n_s = 9.4 \times 10^9$ cm^{-2}. Submultiple resonances with frequencies $f_{c1}/2$ and $f_{c1}/3$ can also be seen [5].

In conclusion, it should be pointed out that experiments on ionic crystals that would highlight the difference between the behaviour of a strongly bound electronic crystal and a weakly bound ionic crystal, are still awaiting to be carried out.

2D electron system above helium

In the case of electrons above helium one can look forward to qualitatively new developments because of the proposal to use these electrons for the diagnostics of electric fields that accompany the flow of a Hall current under conditions corresponding to the quantum Hall effect (QHE). There are still divergent views on the origin of this effect. There is theoretical and experimental evidence of the presence, in the interior of a 2D electron system subjected to a strong magnetic field, of 'bulk' extended electron states. The alternative explanation of the main details of the QHE is based solely on edge electron states in systems of this kind. A discussion of these topics can be found in, for example, the latest review of von Klitzing [10].

Practice has shown that transport measurements are not very effective in identifying the details of the distribution of Hall current density. New methods have therefore been developed for obtaining local information on the distribution of fields and densities in the Hall experiments. The best known among them is the linear electro-optic effect [11, 12], in which the plane of polarisation of light propagating across a heterostructure with an optically controlled gate electrode is rotated by an angle proportional to the difference between the gate potential and the local potential of the 2D electron system. If the diameter of a light (laser) beam is sufficiently small compared with the dimensions of the 2D system, information can be obtained on the distribution of local electric fields which accompany the flow of current through the 2D system under the QHE conditions, as demonstrated in Refs [11, 12]. However, von Klitzing points out [10] that the method used in Refs [11, 12] is still insufficiently sensitive.

In view of this it would be interesting to obtain independent local information on electrostatic fields in the Hall experiments with electrons on a helium film [13]. Let us consider an isolated heterostructure containing

a 2D electron system. Let a helium film cover the surface of this structure and let us distribute surface electrons over this film. Let the geometry of the electron system repeat the geometry of the heterostructure. In the presence of the Hall currents and, consequently, potentials in the heterostructure the electrons on the helium film behave as a screening electrode and should become redistributed along the surface of the helium film. Such a redistribution can be detected optically, since the electron pressure on the helium film would nonuniformly alter its thickness. Similar optical effects that appear on a film of helium when multielectron dimples appear on it have been found to be highly sensitive in the detection of the deformation of the film under the action of the pressure exerted by such a multielectron dimple [1, 14]. Estimates show that this approach can be effective also in studies of the distribution of the potentials in systems with Hall currents.

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From the quantum Hall effect to a Wigner crystal

V M Pudalov

The general relationships governing the appearance of the quantum Hall effect (QHE)—representing transitions between the various phases and transitions from a quantised (metallic) to an insulator state—have become the focal point of recent experiments and of vigorous theoretical debates. The problem is closely related to the global behaviour of a two-dimensional (2D) electron system in the presence of a quantising magnetic field and disorder. A reduction in the electron density n_s tends to order the 2D system so that it forms a crystal lattice because of an increase in the role of the electron–electron interaction energy $E_{ee} = (\pi n_s)^{1/2} e^2/\kappa$ compared with the Fermi energy $E_F = \pi n_s \hbar^2/m^*$. On the other hand, a reduction in the electron density is accompanied by an increase in the relative degree of disorder in the system, which tends to result in a complete localisation of the 2D system. There is a related very interesting problem of the 'termination' of QHE, i.e. of a transition of a system to an insulator phase from the QHE state. In contrast to metal–insulator transitions in three-dimensional systems, in two dimensions there is a unique opportunity to study the behaviour of extended delocalised states and thus establish the exact scanario of the transition to an insulator.

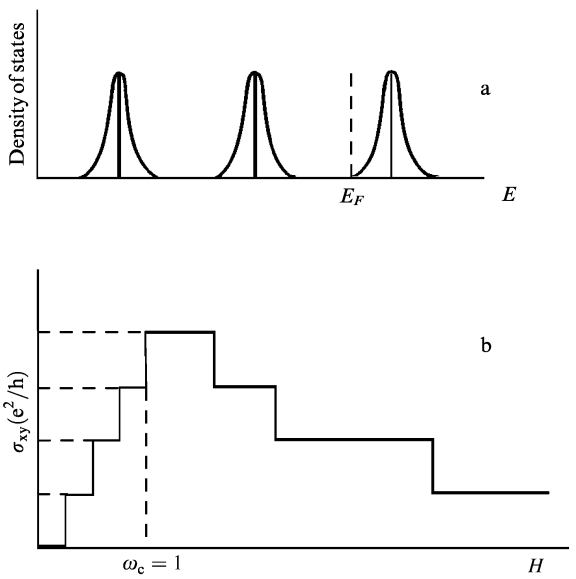

Figure 1. (a) Schematic representation of the density of the 2D states in a quantising field. The thick vertical lines represent the extended states. (b) Dependence of the Hall conductance on a magnetic field, predicted by the scaling theory in the one-electron approximation.

One-electron approach

In the QHE the transport of charge in a quantised 2D system occurs because of the existence of extended Landau states at each level. Against the background of the overall density of states, shown in Fig. 1a, these extended states occupy (as is usual to assume) only a narrow strip in the centre of the Landau band. Each of these states makes a contribution, equal exactly to e^2/h, to the Hall conductance. This means that if there are i extended states below the Fermi level, the conductance amounts to ie^2/h, which corresponds to the ith plateau or the state of the quantum index $s_{xy} = i$. This is true only in the limit of strong magnetic fields when $\omega_c\tau \gg 1$. Halperin [1], Khmel'nitskii [2], and Laughlin [3] have predicted that a reduction of the magnetic field, so that $\omega_c\tau$ becomes ~ 1, should mark the start of the increase of the energy of the nth extended state E_n:

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega_c\left[1 + (\omega_c\tau)^2\right](\omega_c\tau)^{-2} . \qquad (1)$$

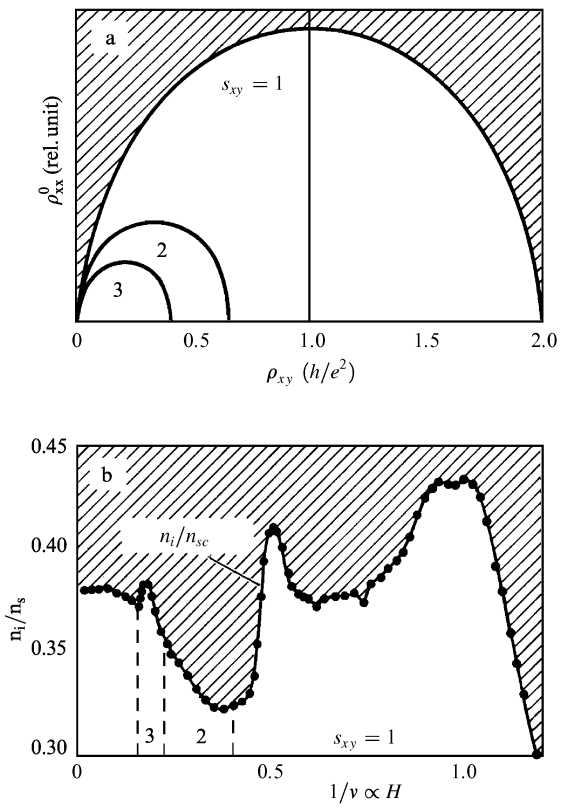

Figure 2. (a) Phase diagram under the conditions of the integral quantum Hall effect [4] (reproduced by kind permission of D-H Lee); the ordinate represents the degree of disorder and the abscissa is the magnetic field. Both these quantities are in dimensionless units. (b) Results of measurements [7, 8] carried out at $T = 35$ mK. The shading represents the insulator phase.

It therefore follows that in the limit $\omega_c\tau \to 0$ such extended states become 'detached' from the Landau levels and 'float up', passing in turn through the Fermi level. When the lowest extended state ($n = 0$, $s_{xy} = 1$) floats up in this way, the system becomes an insulator. According to this scenario of the termination of the QHE, the Hall conductance should vary with reduction in the magnetic field as shown schematically in Fig. 1b. It should be stressed that the Hall conductance and the Hall resistance then lose the single-valued classical and quasiclassical relationship to the density of mobile charge carriers.

Global phase diagram

These ideas have recently been generalised by Kivelson, Lee, and Zhang [4], who have proposed a global phase diagram (Fig. 2a) to describe transitions between various states in a quantised 2D system. The y axis represents the degree of disorder in the system or the 'resistance' and the x axis is the magnetic field in dimensionless units. The outer shaded region represents an insulator phase with $s_{xy} = 0$ which does not contain even one extended state. The insulator region extends right down to the axis of zero disorder at $H = 0$ and also at a half-filled lowest Landau level, which obviously corresponds to the hypothesis of weak localisation. Nestling curves separate regions with different values of s_{xy}, i.e. with different plateaux of the quantised Hall resistance. The transitions from an arbitrary initial state with $s_{xy} = m$ to any other state can occur, in accordance with this diagram, only by a chain of transitions with consecutive changes in the index s_{xy} by ± 1. This applies to transitions which occur as a result of a change in the magnetic field or under the influence of disorder; this corresponds to the motion of mapping points along a horizontal or vertical line in Fig. 2a.

Results of measurements

In experimental studies of the transitions in a two-dimensional electron system it is convenient to use silicon metal–insulator–semiconductor (MIS) structures in which the density of states can be varied by altering the gate voltage. In the work by our team we selected MIS structures with an ultrahigh mobility μ ranging from 5×10^4 to 7.5×10^4 cm^2 V^{-1} s^{-1}, in which a low-density phase (down to 4×10^{10} cm^{-2}) could be created. The results of earlier measurements have shown [5, 6] that the Landau levels in such samples remain well-resolved right down to the actual transition to an insulator. This provides a unique opportunity for the study of the paths of mobile states in the phase diagram when transitions occur between different phases.

Fig. 3 shows a typical dependence of the diagonal R_{xx} and Hall ρ_{xy} resistances on a magnetic field near a metal– insulator transition in a 2D system [7, 6, 8]. When the electron density is sufficiently low, $n_s \leqslant 10^{11}$ cm^{-2}, and temperatures are in the millikelvin range, a typical insulator state is obtained: it is characterised by the overall diagonal resistance (per unit area) $\rho_{xx} \sim 10^{10}$ Ω '$^{-1}$ or more [7]. Several previous investigations [5, 7, 9] have shown that the insulator state is a collective solid phase. However, for the purpose of our analysis it is important only that the state is a real insulator with the following properties: (1) $dR_{xx}/dT < 0$; (2) $\rho_{xx} \gg h/3e^2$; (3) the diagonal conductance σ_{xx} has a sharp threshold in its electric-field dependence [9, 10].

The insulator phase is interrupted by a metallic state in the QHE regime at values of the magnetic field which correspond to the filling of an integral number of Landau levels. If the electron density is kept fixed and the magnetic field is varied, the observed changes in ρ_{xx} appear as a chain of alternate metal–insulator transitions and the insulator phases are strongest near the filling of a half-integral number of Landau levels.

The resistance R_{xx}, plotted in Fig. 3 as a function of H, is not an appropriate measure of disorder, since its value represents also the threshold of the transition to an insulator. Therefore, a comparison with the theory is made in Ref. [6] on the basis of the density of scatterers per electron, n_i/n_s. The experimental points in Fig. 2b are deduced from measurements of the critical density n_c at a metal– insulator transition [7] and $n_i \approx 3 \times 10^{10}$ cm^{-2} is estimated from the mobility [9]. The shaded region in Fig. 2b represents the insulator. The region below the curve corresponds to metallic states in the QHE regime: it is possible to distinguish readily the states with $i = 1, 2, 6$, and the nascent state $i = 10$.

These results apply to a two-valley electron system in (100) Si; in a comparison with theory one can ignore, for the sake of simplicity, the intervalley interaction and consider two noninteracting one-valley systems. When this not very realistic assumption is made, both regions with $i = 1$ and 2 should have the same index $s_{xy} = 1$. Under these assumptions the general form of the experimental diagram in the

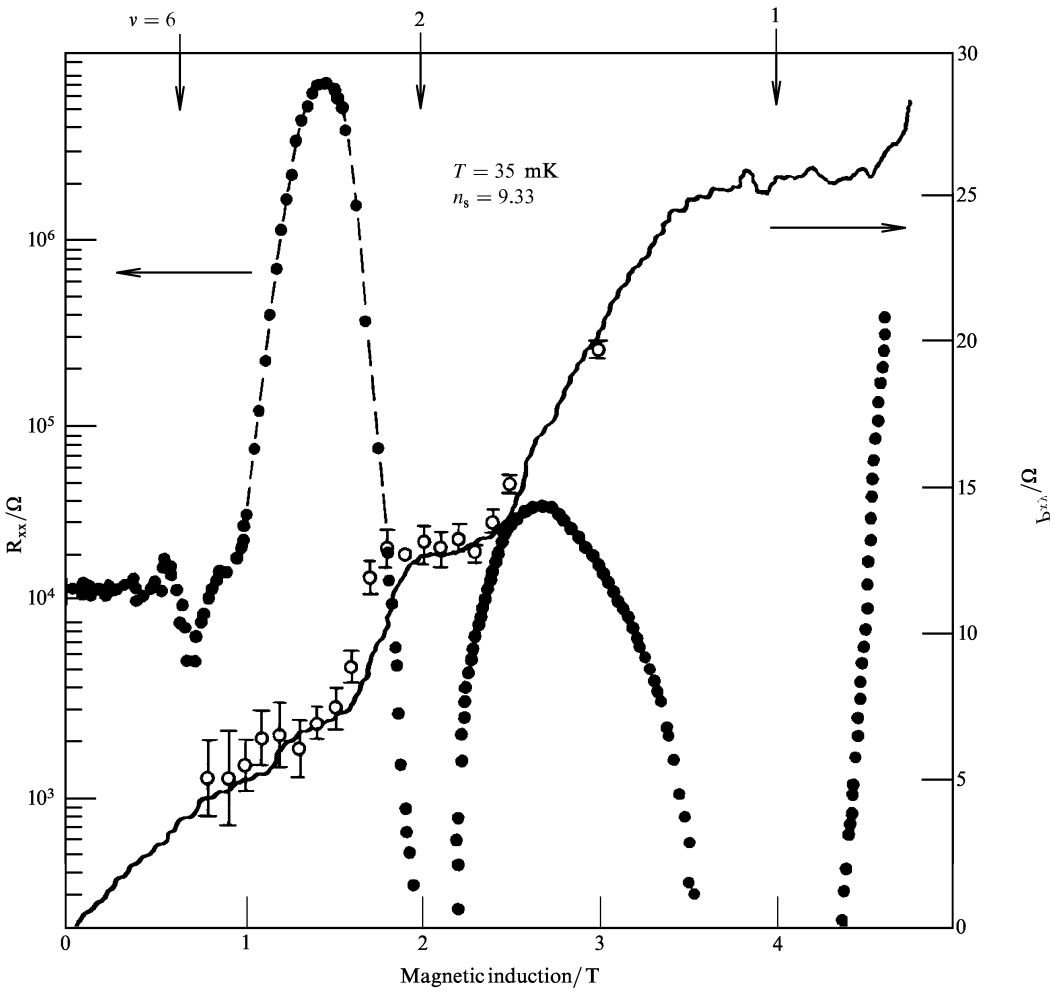

Figure 3. Dependences of the diagonal and Hall resistances on magnetic field in the region of an oscillatory metal – insulator transition [7, 6].

range $2.5 > \nu > 0.8$ slightly resembles the theoretical diagram: there is a peak at $\nu = 1$ and 2 and a fall at $\nu > 0.8$ (ν is a coefficient representing the occupancy of the Landau levels). A more detailed analysis of the experimental data in the extreme quantum limit [12] shows that the metal–insulator transition occurring in strong fields from the lowest Landau level is not in conflict with the hypothesis of the 'floating up' of the extended states across the Fermi level.

However, there is also a fundamental difference between the theory and the diagram in Fig. 2a: the experimental results [6, 10] demonstrate clearly a direct transition from a state with the quantum Hall resistance at $\nu = 6$, i.e. for $s_{xy} = 3$, to an insulator; such a transition is not permitted by the topology of the diagram in Fig. 2a. It follows from the scaling theory [1–3] that such a transition would require the passage of six delocalised states across the Fermi level. This should be accompanied by six anomalies of ρ_{xx} and ρ_{xy}; however, not a single anomaly appears in the experimental results. It remains to conclude that either the various branches of the diagram in Fig. 2a merge into one universal curve in the limit $H \to 0$ and then delocalised states 'float up' in groups, or the observed transition is totally unrelated to such 'floating up'. The first possibility has indeed been suggested [13] and is related to the treatment of the electron–electron interaction as a perturbation. The second possibility is based on the assumption that the electron– electron interaction is the main factor: this will be analysed in greater detail below.

Collective metal–insulator transition

This is the transition which should produce a 'pinned' crystal. The formation of such a crystal does not require that delocalised states pass across the Fermi level, but can remain 'frozen' in the lattice. Experiments involve a study of a transition to an insulator which occurs as a result of reduction in the electron density and not under the influence of an increase in the real disorder at a fixed density. A reduction in the density is accompanied, as mentioned above, by an increase in the importance of the electron–electron interaction.

Fig. 4a shows schematically the boundary between a 2D electron liquid and a solid phase at $T = 0$, plotted in the coordinates r_s and H, where $r_s = a/a_B$ is the radius of a Wigner–Seitz cell and $a_B = 21.4$ A is the effective Bohr radius in (100) Si. Let us see how this boundary should vary with magnetic field on the assumption that, by definition, the chemical potentials of the solid and liquid phases are equal at any point on this boundary. The application of a magnetic field induces quantum oscillations of the chemical potential of the liquid phase, whereas in the solid phase there is no orbital motion of electrons and the chemical

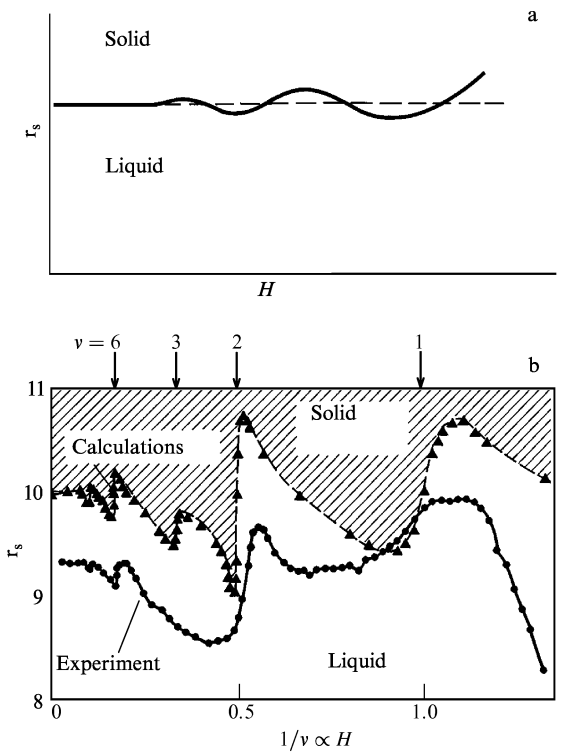

Figure 4. (a) Schematic representation of the dependence of the phase boundary in quantum melting of a Wigner crystal on magnetic field. (b) Theoretical dependence calculated from measurements of the oscillations of the chemical potential (dashed curve) and the results of direct measurements (continuous curve). The numbers with arrows identify the degree of occupancy near the main singularities.

potential is, in the first approximation, independent of the magnetic field. Therefore, to maintain an equilibrium of the phases the actual boundary should experience quantum oscillations in a magnetic field, shown schematically in Fig. 4a. These oscillations of the boundary directly lead to the appearance of alternating metal–insulator transitions if we assume that the density (or r_s) is fixed near the critical value and the field is varied, i.e. that the mapping point is moved horizontally.

This simple idea and earlier measurements of the oscillations of the chemical potential in the liquid phase can be used to plot the boundary of quantum melting [14] shown dashed in Fig. 4b. The following assumptions are made in plotting this boundary:
(1) the critical value is $r_s = 10$ for $H = 0$, in accordance with the recent calculations of quantum melting [15, 16];
(2) the value of the derivative $\partial(E_S^g - E_L^g)/\partial r_s \approx -0.17$ meV is found from a computer simulation [15] of quantum melting in 2D systems (here, E_S^g and E_L^g are the energies of the ground state per particle in the solid and liquid phases, respectively).

The same Fig. 4b gives, for the sake of comparison, the experimental results taken from Refs [6, 8]. Although the dashed curve is plotted without recourse to any fitting parameter, the agreement with the direct measurement r_c (continuous curve) is fairly good in respect of the amplitude and phase of the oscillations of the boundary in the $r_c(H)$ diagram. According to this approach the insulator phase is formed by a 'pinned' electron lattice and escape of extended states is not needed for its formation. It follows that transitions are allowed from any quantised state s_{xy} directly to an insulator state; this is obviously in agreement with experiments. If the density is kept fixed near $r_s = r_c$ and the magnetic field is varied (corresponding to motion along a horizontal line in Fig. 4), the mapping point will repeatedly cross the oscillating boundary and this should give rise to alternating metal–insulator transitions, in agreement with the experimental results [5, 7]. The giant maxima of R_{xx} which are then observed correspond to the insulator phase and the minima of R_{xx} represent the minima of the chemical potential (in contrast to the QHE, in which the maxima correspond to the position of the Fermi level within the energy gap). A more detailed quantitative analysis shows that this model is in agreement with the experimental results.

To conclude, let us consider the oscillatory metal–insulator transitions which terminate the QHE when the density of the 2D electron system is reduced. In the case of silicon MIS structures with ultrahigh mobilities such transitions can be explained quantitatively by quantum oscillations of the boundary representing melting of a collective solid electronic state.

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