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Two Recent Experments on the Fractional Quantized Hall Effect

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Abstract An overview is given of recent transport experiments investigating two outstanding issues in the fractional quantum Hall effect. One is the charge of quasiparticle/quasihole excitations from the fractional quantum Hall liquids; the other is the transition to the Wigner crystal.

Introduction

I shall give an overview of two recent transport experiments investigating two outstanding issues in the fractional quantized Hall effect (FQHE) [1,2], namely, the charge of the quasiparticles from the FQH liquids and the transition to the Wigner crystal at sufficiently small Landau level fillings. One is the observation of resistance fluctuations in narrow samples, showing evidence for the e/3 charge of the quasiparticle/quasihole excitations from the 1/3 FQH liquid. The other is a systematic study of I-V and low frequency noise in the recently identified reentrant insulating phase around the 1/5 FQH liquid, with results consistent with identifying the insulator as a weakly pinned Wigner solid. My emphasis is on how the main features in the transport characteristic evolve, as the amount of disorder decreases in the sample, to stress the importance of random potential in this problem.

The Two-Dimensional Electron Gas in Heterostructures

The free charge carriers (electrons or holes) confined to move along the hetero-interface of two different semiconductors constitute a unique, nearly ideal two-dimensional electron system (2DES). The electronic motion perpendicular to the interface is quantized and the energy of quantization (typically several tens of meV for a GaAs electron confined to the GaAs/$Al_xGa_{1-x}As$ interface) is sufficiently large that the electronic motion is strictly 2D at the relevant experimental temperatures. The single particle energy spectrum of such an idealized 2DES in a magnetic field B is a series of discrete Landau levels separated by cyclotron energy, each with an orbital degeneracy $N_\phi = B/\phi_o$, where $\phi_o = h/e = 4.14 \times 10^{-7}$ G$-$cm^2. The FQH liquids are the special ground states resulting from removal of this extremely high degree of orbital degeneracy of the Landau level ($\sim 2.4 \times 10^{11}/cm^2$ at B = 10T) by electron correlation. On the other hand, the free carriers are from donor (or acceptor) impurities intentionally placed in the structure at some distance (hundreds of Å, e.g.) from the 2D layer [Fig. 1(a)]). The granularity of these doping impurities ($\sim 10^{11}/cm^2$) and also the unavoidable charged defects ($< 10^{14}/cm^3$) throughout the structure gives rise to a potential fluctuation in the 2DES, whose strength, range and randomness (determined by the charged impurity configuration) is, to a large extent, unknown and uncontrolled. As a result, each Landau level is broadened into a subband [Fig. 1(b)] and the relevant physics is that of an interacting 2DES in a strong B field in the presence of disorder; it is fundamentally interesting, but expected to be difficult and perhaps complicated.

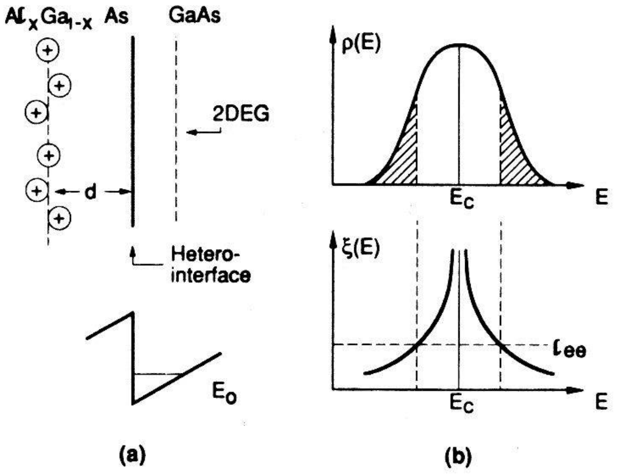

Fig. 1: (a) Two-dimensional electron gas (2DES) in a GaAs/Al_xGa_{1-x}As heterostructure and its representation in a band diagram. (b) Illustration of the density-of-states $\rho(E)$ and localization length $\xi(E)$ of a Landau subband. l_{ee} is postulated T = 0 electron-electron interaction length parameter. The shaded regions indicate localized state which have $l_{ee} > \xi$.

Quantum Hall Effect

The FQHE and the integer quantum Hall effect (IQHE) [3] are direct experimental manifestations of the fundamental physics of 2DES in two different limits. In the dirty limit, when disorder dominates and the 2D electron mobility is relatively low, only the IQHE is observed [4]. The effect of electron-electron interaction is unimportant and the physics of the 2DES is primarily the localization physics of non-interacting 2D electrons in B and in a random field. Fig. 2 is an example of IQHE data [5], plotted as a function of B. As B is swept down from

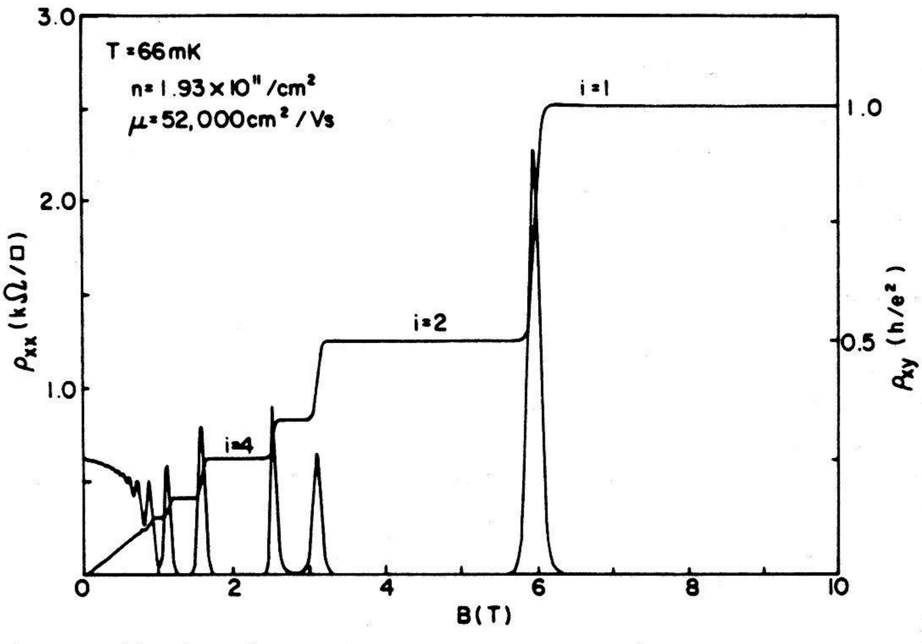

Fig. 2: ρ_{xx} and ρ_{xy} vs B taken from a lower mobility GaAs/Al_xGa_{1-x}As sample (from Ref. 5).

the high B end, for instance, it decreases the Landau level degeneracy and thus increases the filling factor $\nu \equiv n/N_\phi$ (where n is the 2D electron density). As a result, the Fermi energy E_F

is moved through the single particle energy spectrum of successive Landau subbands. In the range of B, where the Hall resistance shows quantized plateaus ($\rho_{xy} = h/ie^2$ and i are integers) and the diagonal resistivity ρ_{xx} becomes vanishingly small, the states at E_F are localized. The transition regions between two neighboring plateaus, where ρ_{xx} shows peaks of finite widths, indicate that the states at E_F are extended. The physical picture that has emerged from the studies of the T dependences of this transition region in recent years is that the T = O localization-delocalization transition can be described by the divergence of the electron localization length ξ, as E_F approaches the transition through $\xi \sim |E_F - E_c|^{-\nu}$, where E_c is close to the unperturbed Landau level energy [6-9]. In other words, in a large size sample at T = O, all states, except for those at the singular energy E_c in the Landau subband, are localized and the localization-delocalization transition is close to $\nu = 1/2$.

The FQHE results from a special correlation of the 2D electrons motion to minimize the Coulomb repulsion energy. The phenomenon is observed in sufficiently high mobility samples first at $\nu = 1/3$ and $2/3$ and more recently at increasingly smaller fillings (Fig. 3) as the disorder in the 2DES is further reduced [10,11]. This experimental fact is suggestive of the notion that as disorder is reduced and the electron-electron interaction becomes more dominant, the electron states in a finite range of energies around E_c become delocalized [Fig. 1(a)]. This range of delocalized states increases with decreasing disorder. A simple heuristic picture to incorporate this result is the postulate that the electron-electron interaction effect may be parameterized by an interaction length l_{ee} at T=O and the single particle states at a given energy is delocalized if $\xi > l_{ee}$, as illustrated in Fig. 1(b).

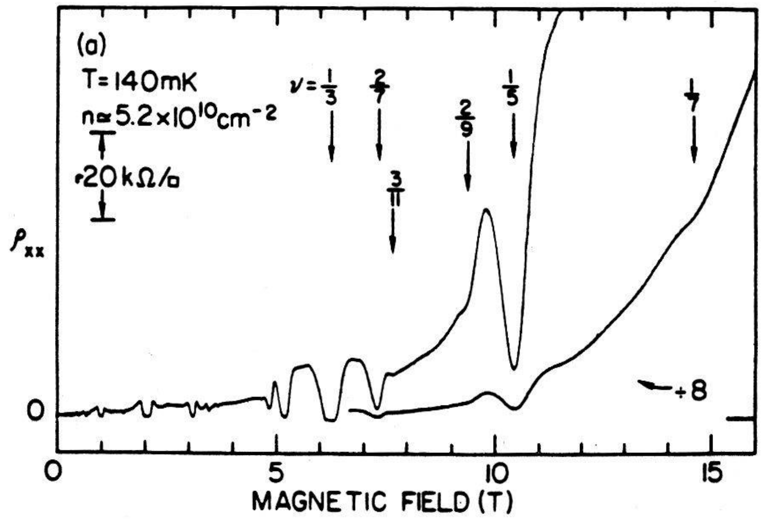

Fig. 3: ρ_{xx} vs B from a low disorder $GaAs/Al_xGa_{1-x}As$ sample, showing FQHE at Landau level fillings $\nu < 1/3$ (from Ref 10).

Fractional charge

Several recent experiments have attempted to determine the charge of the quasiparticle/quasihole excitations of the FQH liquids [12-14]. The one I want to mention is a study of the resistance fluctuations in a narrow sample, due to breakdown of the dissipationless current flow by resonant tunneling via states magnetically bound to the potential hills and valleys in the 2DES [15,16]. In the semiclassical limit, when the cyclotron diameter is much smaller than the size of the potential, the n^{th} energy level of the bound states is determined by Bohr-Sommerfeld quantization of the action integral:

$$e^*\phi_n = nh \tag{1}$$

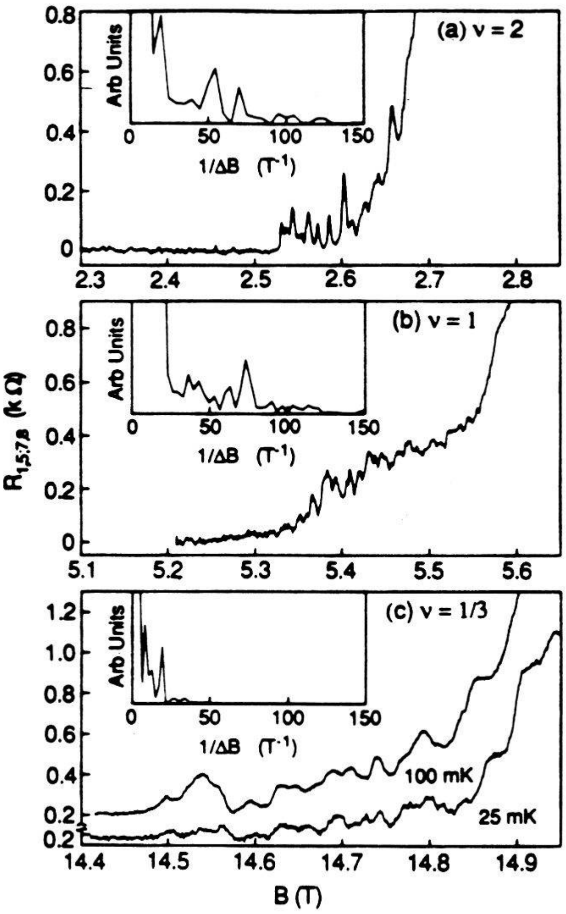

Fig. 4: The resistance along current flow, $R_{1,5:7,8}$, near the high field sides of resistance minima for (a) ν = 2 at 25mK, (b) ν = 1 at 25mK, and (c) ν = 1/3 at 25 and 100mK, all plotted with the same field scale. Insets show the Fourier power spectra of the region of fluctuations for each respective ν (from Ref. 14).

where ϕ_n is the magnetic flux enclosed in the n^{th} allowed orbit and e* is the charge of the quasiparticle. In a uniform B, $\phi_n = BA_n$ and A_n is the area of the orbit. In the experiment [14,17], quasi-periodic noise structures are observed in ρ_{xx} for B adjacent to the quantized Hall plateaus in narrow samples of a high mobility 2DES. Fig. 4 is an example of the data showing the resistance fluctuations as a function of B. While the period is $\sim$ 150 G for the structures adjacent to all the IQHE plateaus (shown in the top two panels for $\nu = 2$ and $\nu = 1$, respectively), an approximately three times larger period ($\sim$ 500 G) is observed for the structures adjacent to the $\nu = 1/3$ FQHE plateau. It has been demonstrated that the effect is local and close to a particular set of potential probes and can be attributed to tunneling via magnetic bound states submicron in size. The dependence of the fluctuation amplitude on temperature and current [18] indicates that Coulomb blockade [19] is not relevant to the experiment.

In the more recent experiment [17], the 2D electron density can be varied by applying a backgate bias V_G to the sample and, as a result, the fluctuations are studied as a function of V_G as well as B. In Fig. 5 the quasiperiods ΔV_G and ΔB are plotted as a function of T and we find:

$$\Delta B(\nu = 1/3) = 3\Delta B(\nu = 1) = 3\Delta B(\nu = 2) \tag{2}$$

and

$$\Delta V_G(\nu = 1/3) = V_G(\nu = 1) = 1/2\ \Delta V_G(\nu = 2)\ . \tag{3}$$

This result is consistent with the model of resonant tunneling via states magnetically bound to some potential hill in the 2DES and demonstrates that the charge of the bound quasiparticle/quasihole excitation of the 1/3 FQH liquid is e/3. In this model, a resistance peak occurs whenever a bound state is aligned with the chemical potential μ of the relevant edge channel. The fluctuation period in the B sweep data, given by the change in B needed to align the next bound state with μ, is:

$$\Delta B = \Delta\phi_n[d(BA_n)/dB]^{-1}\ . \tag{4}$$

In the IQHE case, $\Delta\phi_n = \phi_{n\pm1} - \phi_n = \pm\ h/e$. Consequently, ΔB is the same for all integer ν (if dA_n/dB is negligible), in agreement with experiment. In the V_G sweep experiment, the period given by the change in μ to align the next bound state is:

$$\Delta V_G = \Delta\phi_n[d(BA_n)/dV_G]^{-1}\ . \tag{5}$$

Since the fluctuations for the $\nu = 1$ minimum is observed at twice the B for the $\nu = 2$ fluctuations, the observed $\Delta V_G(\nu = 1) = (1/2)\Delta V_G(\nu = 2)$ relation is expected from the model. On the other hand, if the semiclassical orbits are assumed by the quasiparticles in the 1/3 FQHE case, e^* in the quantization condition is e/3 and $\Delta\phi_n = h/e^* = 3h/e$. As a result, ΔB at $\nu = 1/3$ should be three times that at $\nu = 1$ and ΔV_G, because the fluctuations for $\nu = 1/3$ is observed at a three times higher B, should be the same as that at $\nu = 1$.

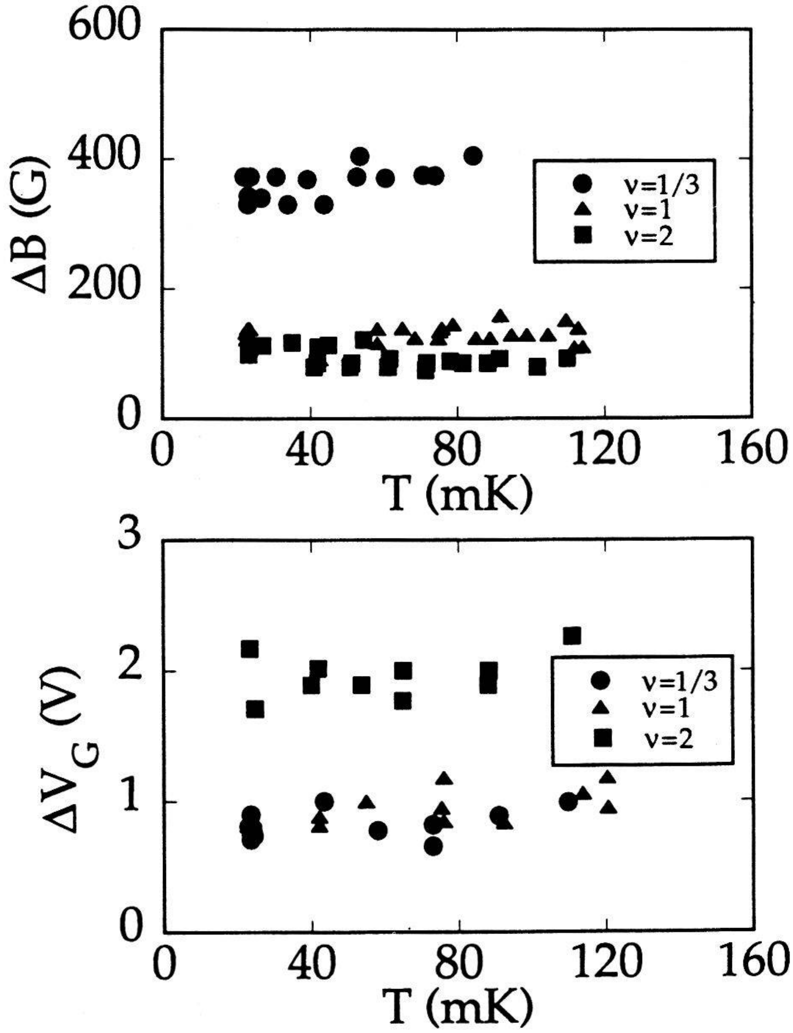

Fig. 5: Fluctuation periods ΔB and $\Delta\ V_G$ vs T (from Ref. 17).

Termination of the FQHE Series

It has long been anticipated that in the sufficiently small ν limit, a triangular Wigner crystal is favored over the FQH liquids. Moreover, random impurities are expected to pin the electron crystal to the host semiconductor and, as a result, the 2DES should be an insulator.

Experimentally, thermally activated conduction, indicative of an insulating state, is apparent for $\nu < 1/3$ even in the earliest FQHE data and subsequent studies have identified an onset for this insulating behavior at $\nu \sim 1/4$ in lower disorder 2DES [20]. However, it has been extremely difficult to tell if the insulating state is indeed due to the pinning of a solid and not Anderson localization of single particles in the extreme quantum limit. Only very recently Jiang et al. [11] has obtained data showing clear evidence that in sufficiently low-disorder 2DES the ground state at $\nu = 1/5$ is indeed a FQH liquid and, therefore, the insulating state observed for filling slightly above $\nu = 1/5$ cannot be due to single particle localization. It must be the result of electron-electron correlation.

Fig. 6 shows the data from Jiang et al. At $\nu = 1/5$, ρ_{xx} decreases exponentially with decreasing T down to the lowest available T (inset of Fig. 6). The data demonstrate for the first time that in a sufficiently clean 2DES the 1/5 state is a true FQH liquid in that $\rho_{xx} \rightarrow 0$ as $T \rightarrow 0$. Surprisingly, in a small region for $\nu > 1/5$ (e.g. $\nu = 0.21$), $\rho_{xy} > \infty$ as $T \rightarrow 0$, indicative of an insulator at $T = 0$, and is similar to that for ν immediately below 1/5. The fact that this insulating state is observed at ν above the 1/5 FQH liquid suggests that it results from electron-electron correlation and a pinned Wigner solid is a distinct possibility. The experiment further suggests a reentrant phase diagram above and below $\nu = 1/5$.

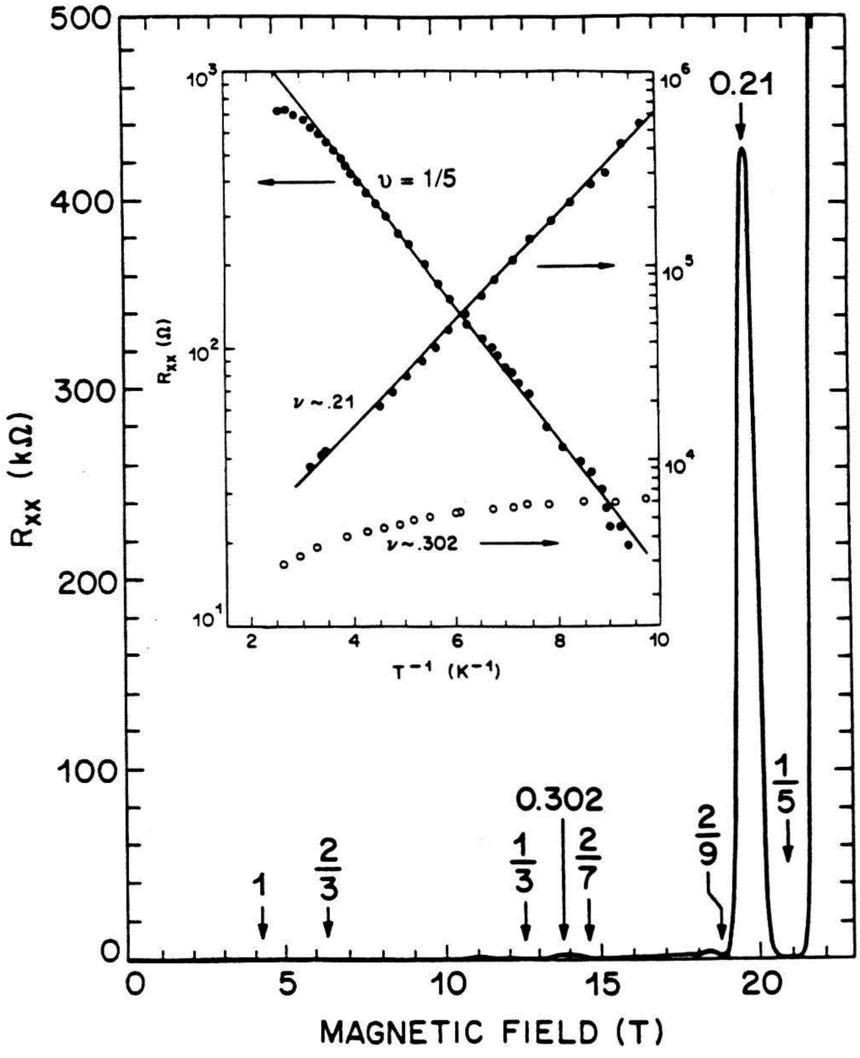

Fig. 6: Diagonal resistance R_{xx} vs B at 90mK. Inset: Arrhenius plots of R_{xx} at $\nu = 1/5$, 0.21 and 0.302 (adapted from Ref. 11).

Presently, there is a great deal of experimental interest in this problem [21-25]. The systematic study of I-V and low frequency noise in this reentrant insulating phase, which I mentioned, has appeared elsewhere [23]. In addition to dc transport experiments, high frequency and optical measurements have now been more thoroughly exploited [24-27]. A variety of striking anomalies have been reported in different experiments on similarly low disorder 2DES in this insulating phase below $\nu \sim 1/4$ [28]. However, in spite of some circumstantial evidence, there does not exist an experimental study which can possibly identify the sought after electron solid. The nature of this insulating phase (or perhaps phases) is not yet clear at this moment. For example, in analogy with conduction due to depinning of the charge-density-waves in materials such as $NbSe_3$, onset of nonlinear I-V has been taken as evidence for sliding of the solid. However, very different nonlinearity and onset threshold have been reported and it is not clear whether sample geometry and inhomogenity and possibly thermal runaway may play some important role. Narrow band noise, which can be direct evidence for the existence of periodic electron lattice, has not been observed to date and the preliminary results of Shapiro steps in an ac/dc mixing experiment [29] has yet to be reproduced in samples with better defined nonlinear conduction threshold. Equally unclear is the reported melting transition phase diagrams. The rf experiment of Andrei et al. [30] is now believed to measure the pinning of the electron solid. Similar to an earlier experiment by Wilson et al. [31], it may only probe the random potential, not the shear of the 2DES. Thus, I find it reasonable to conclude at this time that there is plenty of experimental evidence that we have entered into a new regime of the 2DES, where the correlation and localization physics seems to manifest in phenomena markedly different from the familiar and the anticipated. However, conclusive evidence for the Wigner crystal is still missing.

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