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Wigner crystals in transition metal dichalcogenides

1. **Signatures of bilayer Wigner crystals in a transition metal dichalcogenide heterostructure**
   Authors: You Zhou, Jiho Sung, Elise Brutschea, Ilya Esterlis, Yao Wang, Giovanni Scuri, Ryan J. Gelly, Hoseok Heo, Takashi Taniguchi, Kenji Watanabe, Gergely Zaránd, Mikhail D. Lukin, Philip Kim, Eugene Demler, and Hongkun Park
   arXiv:2010.03037

2. **Observation of Wigner crystal of electrons in a monolayer semiconductor**
   Authors: T. Smoleński, P. E. Dolgirev, C. Kuhlenkamp, A. Popert, Y. Shimazaki, P. Back, M. Kroner, K. Watanabe, T. Taniguchi, I. Esterlis, E. Demler, and A. Imamoğlu
   arXiv:2010.03078

Recommended with a Commentary by Thierry Giamarchi, University of Geneva

Among the large set of phases that interactions can produce with the electron gas, one of the earliest prediction [1] made by Wigner was the one of a crystallization of the electronic system, due to long-range Coulomb interactions. Indeed in order to minimize the Coulomb repulsion it is preferable, if the kinetic energy of the particles is sufficiently low – which usually means low density of particles –, to replace the usual plane wave (or their interacting equivalent in a Fermi liquid) by concentrated wavepackets around well defined positions in space. This is bad from the point of view of kinetic energy but favorable to minimize the Coulomb repulsion. In that case, the electrons would form a regular lattice – hexagonal in two dimensions, since it is the one with the largest distance between particles at fixed density. This very interesting electronic phase, the Wigner crystal, has several interesting and unique features

- It breaks the translational symmetry of the system without the need of a lattice, at variance with e.g. Mott insulators. It gives a crystal with large distance between sites much larger than the true lattice crystal.

- It does not involve additional degrees of freedom, such as phonons for the Charge-density waves instabilities. As a result the wavepackets localized are essentially electrons, with a very small mass and thus still very strong quantum effects.

- As a result the Wigner crystal is both "classical" in the sense that particules are now essential discernible by their position, so fermionic character plays a much less important role than in the Fermi liquid, and "quantum" in the sense that there are severe quantum fluctuations of the particles, leading to very interesting properties for this quantum crystal.

- The lattice spacing of the crystal can be controlled by changing the density of carriers, making it "easy" to change its properties and in particular to induce melting.

- The crystal can be set in motion by applying an electric field. The motion gives rise to a current.

- The crystal is embedded into a real crystal, which means that it can be subjected to *external* perturbations such as disorder which will affect both its equilibrium properties (lattice structure) and its transport properties since the crystal will pin much more easily on the disorder than an electronic liquid would.

Such a remarkable quantum crystal has thus stimulated a hunt to observe it experimentally. However this is not so easy: i) densities at which the crystallization is supposed to occur are extremely low; ii) the material must be clean enough so that the external disorder does not break the crystal too much.

First indications of the existence of a Wigner crystal came from semiconducting structures in which the fractional quantum hall effect had been observed. These systems had two advantages: i) they were quite clean with only weak disorder; ii) the strong magnetic field helped killing the kinetic energy (the electrons run in circles in Landau orbits) thus helping to reach crystallization at higher density (even if still pretty low of the order of $n \sim 10^{11}$ e cm^{-2}).

One important question is how to decide on the presence of such a Wigner crystal since imaging is difficult (the electronic structure is buried deep in the whole device). One has thus to resort to indirect measurements. Those were provided by soundwave absorption showing resonance at the modes of the crystal [2] or the observation that both longitudinal and transverse resistivity diverged above a threshold of magnetic field [3]. Of course the later measurement indicated that the crystal was pinned by disorder, prompting for very interesting questions of the effect of the disorder on the very structure and properties of the crystal itself. Further measurements of the current-voltage characteristics showing a critical voltage below which no current appeared [4] confirmed this pinned crystal interpretation. Further and quite conclusive proof of the existence of a Wigner crystal under magnetic field was provided by optical conductivity measurements [5] showing a resonance peak at a characteristic frequency (pinning frequency) due to the combination of the elastic structure and the external disorder. The magnetic field and density dependence of this peak were in agreement with the expectations for such a Wigner crystal [6]. In addition to showing the existence of the crystal itself, these measurements showed also the potential of pinned Wigner crystals to test some of the aspects of pinned quantum elastic structures (more details on these aspects and further references can be found in the review [7]).

Finding a Wigner crystal without a magnetic field was a strong challenge, since lower densities by about one order of magnitude were a priori needed. A potential system was given in similar semiconducting systems [8] that showed an insulating phase at low densities. Further measurements in particular of the noise [9] was consistent with the interpretation of this insulating phase in terms of a pinned Wigner crystal.

So the semiconducting structure such as GaAs provided good potential for the realization and observation of a (pinned) Wigner crystal, but most of the experiments: i) were probing the existence of such crystal via transport measurements; ii) the experiments were also confined in an extreme range of temperatures, densities and magnetic field in order to be in the proper phase.

The two papers discussed in this journal-club show that there is a new player in town, which nicely complements the former semiconducting structures and give access to different range of temperatures, magnetic fields and even observational techniques. The two papers deal with transition metal dichalcogenides such as $MoSe_2$. These systems form nice two dimensional structures. The first paper deals with a bi-layer of such material while the second one looks at a monolayer. Both papers argue convincingly for the formation of a Wigner crystal in such structures. One of the main differences compared to e.g. GaAs is the much larger mass of the particles, that allows for a more efficient killing of the kinetic energy and thus to reach the Wigner crystal phase without the help of the magnetic field and at much higher temperatures.

For the monolayer system, the presence of the Wigner crystal is investigated by looking at a resonance in the absorption of an exciton which is attributed to the presence of an umklapp scattering on the periodic structure of the Wigner crystal. The presence of the resonance is thus taking as a proof of the existence of the WC phase. This indirect observation is a little bit reminiscent of the sound wave absorption of [2]. Although the evidence is somewhat indirect the density dependence of this resonance, which should scale with the density (since the lattice spacing changes), is quite convincing. Temperature is still pretty low (of the order of 80 mK, but the Wigner crystallization can be reached without magnetic field. The magnetic field can then be used as an extra knob.

In the bilayer system, only the insulating or metallic nature of the phases is probed so Wigner crystallization is implicitly assumed but in agreement with theoretical predictions for the phase diagram of the system. Quite interestingly in that case (cf. Fig. 4 of this paper) Wigner crystallization is expected for temperatures as high as $\sim$ 40K and for densities in the range $n \sim 10^{12}$ e cm^{-2} which should open a broad range of phase space to study some of the other effects discussed above (effects of pinning, etc.).

So these new systems are a welcome addition to the panoply of devices in which Wigner crystallization can be observed. In addition to giving access to a whole new range of densities and temperature the have shown that new probes can also be used to study their physics. It would be in that respect interesting to see if a direct imaging of the crystal would be more easy in such systems (the electron gas seems to be more accessible than in the previous structures). They certainly offer a very nice field to study the combined effects of disorder an quantum crystal which is at the heart of the theoretical challenges for such systems. For that it will be interesting to see how one can also use the “old” probes such as transport, both d.c. and a.c., or the measure of nonlinear current-voltage characteristics in such systems.

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