Melting of a 2D Quantum Electron Solid in High Magnetic Field

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http://arXiv.org/cond-mat/0604004)

Recommended and Commentary by Thierry Giamarchi, University of Geneva

One would imagine that solids, liquids and how to go from one to the other is by now a well understood problem. In fact even for standard solids the situation is not very rosy, and getting a good theory of melting is difficult. However for three dimensional systems the transition is first order and thus sufficiently brutal so that phenomenological criteria can be used. One such criteria is the Lindemann criterium that states that a solid melts when the relative displacements of two neighbors becomes a certain fraction C_L (so called Lindemann number, usually of the order of $C_L \sim 0,1$) of the lattice spacing a, $\langle [u_{i+1} - u_i]^2 \rangle \propto C_L^2 a^2$. Essentially melting is controlled by short lengthscales. For classical crystals the main source of fluctuations is of course the thermal one. The criteria thus becomes

$$\frac{T_m}{c(a)} \propto C_L^2 a^2 \tag{1}$$

where $c(a)$ are the elastic constants (in general dependent on the distance between particles). Thus, if the elastic constants depend only weakly on the lattice spacing one has the paradoxical prediction that the melting temperature T_m decreases as the system becomes denser. These predictions were well verified for the melting of the vortex lattice in type II superconductors. Note that T_m is mostly controlled by the lattice spacing. In two dimensions one has a quite different mechanism: the Beresinskii-Kosterlitz-Thouless melting, where the melting is controlled by the injection of dislocations at large lengthscales. But here again similar conclusions are reached. So one could think that all is at least qualitatively understood.

However our knowledge of melting is only as good as our knowledge of the "solid" and "liquid" phases. In that respect two ingredients are essential to take into account, namely disorder and quantum effects. Indeed one has a particular class of “crystals” such as vortex lattices in type II superconductors, that can be embedded in an *external* disorder, and thus quite different from the standard case. The main surprise in that case was that the naive expectation that disorder destroyes the solid (hence wiping out the first order melting phase transition) was simply incorrect. The solid was indeed destroyed, but the resulting phase, the Bragg glass, retaines enough quasi-long range positional order to still melt via a first order phase transition much like a pure solid. These results were again in very good agreement with experiments. One very important question was thus how are all these effect modified if one does not consider classical crystals but quantum crystals.

The search for quantum crystals is of course a long and challenging quest in condensed matter. Canonical examples in that respect come from Helium crystals. Another interesting realization is provided by electronic crystals. Such crystals are a manifestation of strong interaction between the quantum particles that favor localized solutions compared to simple plane wave states. One famous example is the Wigner crystal where the repulsion between the electrons can induce crystallization. Another way to enhance the effects of interactions is to kill the kinetic energy with a magnetic field. How one goes from the weakly interacting electron system to the crystal, and what is the nature of the crystal phase is of course a very difficult and interesting problem with bearing on the questions of the interplay of disorder and interactions in electronic systems and to the physics of glasses (for more details see e.g. cond-mat/0403531 and refs therein). In addition these electronic crystals and glasses offer important differences compared to the case of the canonical examples of Helium crystals: i) The forces among the particles are of course very different; ii) The distance between particles can be controlled at will by changing the density (e.g. with a gate voltage). This is quite different from a normal crystal where the distance between the particles is strongly constrained by the atomic forces and can vary very little. In addition to controlling the density itself, for electronic crystals one can also independently control the “size” of the particle, since it represents the size of the localized wavefunction at a given site. For Wigner crystals this can be done by varying a magnetic field. There is thus a unique possibility to “engineer” the crystal at will; iii) Very importantly the electronic crystals are embedded in the matrix of the real microscopic crystal, and thus can also be subjected to an *external* disorder. This disorder can even exist at lengthscales much finer than the electronic crystal spacing. This is a unique property, totally absent for normal crystal since for them disorder can only be external impurities, vacancies etc. and thus exist at much larger lengthscales than the lattice spacing. The presence of such an external disorder drastically affects both the solid and liquid phases, and thus a priori can change radically the melting properties.

There were many studies undertaken in systems of two dimensional electrons under magnetic field to see if such a phase could be obtained and what are its properties. In particular a.c. conductivity data could show quite convincingly that there was indeed formation of a Wigner crystal, pinned by the disorder present in the system. It was thus very important to address the question of how this crystal melts. The paper recommended addresses this question, by monitoring the resonance observed in the a.c. conductivity that is characteristic of the crystal phase. The main result is that the melting is quite different from what is expected of classical melting. The melting temperature seems to depend *only* on the Landau level filling factor and not simply on the lattice spacing as could be expected from a standard thermal melting.

The fact that both the cyclotron radius r_c *and* the lattice spacing a enter in the melting temperature is of course the sign that the quantum aspects are important in such a system, and that the size of the wavepacket representing one "atom" of the crystal does matter. What are the minimal ingredients needed to understand such a melting is an open and exciting question. Does one need to have a good control on the liquid phase (the Laughlin fluid of fractional quantum Hall effect for example) on the other side of the transition to make predictions on the melting or can one understand such melting directly from the crystal side? It is clear that getting correctly the critical properties of the transition is a complicated question for which the knowledge of the two phases ("crystal" and "Liquid") is needed. On the other hand to correctly predict the *position* of the transition one would expect that simpler criteria similar to the Lindemann one can be established. What these are remains to be determined.

The paper also discusses the effect of disorder, which pushes the melting temperature upward. Note that contrary to what is asserted in the paper, this effect is in good agreement with what is observed for the thermal melting of crystals in the presence of disorder, but *columnar* disorder, not crystals with point like defects (that indeed push the melting temperature down). This fact gives in fact even more credence to the idea that what is observed is indeed the melting of a *quantum* crystal. Indeed in that case the time acts as an extra dimension and the melting of the two dimensional quantum crystal + point disorder, is similar to the a $2+1$ crystal made of lines (along the time direction) and subjected to columnar (i.e. time independent) disorder. Such a problem is known as the Bose glass in the context of vortex lattices. In that case increase of melting temperatures with columnar disorder has been experimentally observed. How much one can go beyond this qualitative agreement and get closer to quantitative predictions for this *disordered* quantum crystal is of course a very interesting question.