CONDENSED MATTER PHYSICS

Watching electronic ice melt

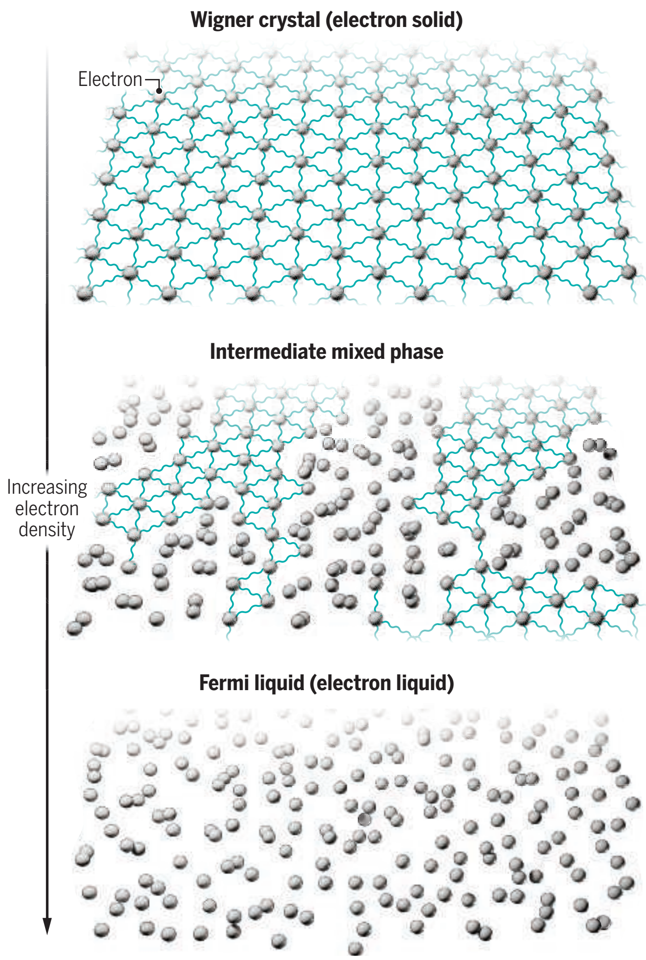
An experiment captures images of the transition between liquid and solid states of an electron system

Sandeep Joy[1,2] *and* **Brian Skinner**[3]

One of the most familiar phase transitions on Earth is the freezing and melting of water. Underlying this transition is the competition between the kinetic energy of water molecules and the potential energy arising from their mutual interactions. When the temperature falls below the freezing point, the interaction energy wins this competition and water freezes. A two-dimensional (2D) system of electrons exhibits a similar competition between kinetic and potential energies that also gives rise to a freezing–melting transition. However, the nature of this transition in an electron system has remained mysterious for decades. On page 736 of this issue, Xiang *et al.* (*1*) report direct imaging of the melting and freezing of a Wigner crystal—a periodic 2D lattice of strongly interacting electrons. The observed intricate spatial patterns raise fascinating questions about the nature of this fundamental phase transition in the quantum realm.

Quantum melting and freezing of electrons

A two-dimensional (2D) system of electrons solidifies at low electron densities in a process known as Wigner crystallization. The electron solid melts into liquid through an intermediate stage in which islands of solid domains are surrounded by liquid phase.



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As in water, the liquid and solid phases of the 2D electron system are unusual in that the solid phase has a lower density than the liquid phase. Unlike water, however, transitions between liquid and solid phases in an electron system can occur at absolute zero temperature. The electrons' kinetic energy arises from quantum mechanical fluctuations—jittering of the electron positions due to quantum mechanical uncertainty. This quantum kinetic energy drops more quickly with decreasing electron density than does the strength of the electrons' interactions, causing the electron system to freeze below a critical density. Such a transition, called Wigner crystallization, was predicted theoretically in 1934 (*2*), but it has been notoriously difficult to realize experimentally. The magnitudes of both the interaction and kinetic energies are small at the transition, and the delicate interplay of these energies is easily interrupted by finite-temperature effects or disorder. Previous studies that imaged Wigner crystals relied on the use of an additional stabilizing force such as a periodic structural modulation (*3*) or a strong magnetic field (*4*) that modified the nature of the phase transition.

There is also a more fundamental difficulty associated with observing the Wigner crystallization transition. When water freezes, large chunks of ice can be seen floating in water. But such macroscopic phase separation is effectively prohibited in an electron system by the long-range Coulomb interactions between electrons. Solid and liquid phases of the electron system have different densities of electrons, whereas the positive background charge that neutralizes these negative charges has a uniform density. Thus, a macroscopic domain of either phase would have a large total charge that is proportional to the area of the domain, and consequently enormous electrostatic forces would act to rip these domains apart, making macroscopic phase separation impossible. An important question, then, is how the electron system can change from one phase to another. One proposed answer is that electrons freeze by passing through a series of microemulsions (*5*–*8*) in which solid and liquid phases are tightly mixed or marbled together. Alternatively, the freezing transition could be dominated by disorder that smoothly modulates the spatial density of electrons. In this scenario, regions with low electron density become solid, whereas other regions with high electron density remain liquid (*9*, *10*).

Xiang *et al.* used noninvasive scanning tunneling microscopy to directly image freezing and melting of a 2D system with a low density of electron holes (a vacancy in an electronic orbital that behaves as a positive counterpart to the electron) in bilayer molybdenum diselenide. The observations showed that near the critical hole density associated with the melting and freezing transitions (analogous to the critical electron density), the system separated into a random pattern of alternating solid and liquid regions that are typically tens of nanometers in diameter (see the figure). The solid regions exhibited a crystalline lattice pattern of holes, whereas the liquid regions displayed a nearly uniform hole density. Varying the overall hole density of the system caused these regions to grow and shrink, with the system becoming either a uniform solid phase or uniform liquid phase far from the critical density. However, the range of hole density over which a phase mixture was observed was larger than the nominal upper bound for the microemulsion scenario by more than an order of magnitude (*11*). This indicates that the disorder-free microemulsion theory does not describe the experiment. At the same time, a key prediction of the disorder-driven scenario was also not borne out because both liquid and solid regions always had essentially identical hole densities.

The study of Xiang *et al.* presents a challenge to existing theories about the Wigner crystallization transition but also provides important clues to resolve this puzzle, particularly through watching the "quantum densification" and "quantum melting" processes. In quantum densification, the hole density of the solid phase changed when additional holes were injected into the sample. Xiang *et al.* noticed that, rather than producing a smooth reduction in the lattice spacing between holes, densification occurs through an abrupt reconfiguration of a small local region (just a few holes wide), similar to when a new person enters a crowded elevator. In quantum melting, the solid phase transforms to liquid when the hole density is brought above the critical value. Xiang *et al.* show that this melting occurs by a process in which solid islands shrink and are gradually inundated by surrounding liquid regions as the hole density increases. These findings suggest that certain hole positions are pinned in place, presumably by impurities in the sample, which play a crucial role in the freezing and melting processes.

At present, there is no established theory that can explain the spatial patterns imaged by Xiang *et al.* The process by which a 2D crystal of electrons (or holes) melts or freezes may involve an intricate interplay between disorder and interactions. Perhaps the experimentally observed patterns are best described as a disorder-precipitated microemulsion, similar to how certain molecules in air can seed the formation of clouds. Indeed, Xiang *et al.* showed that the samples have a noticeable concentration of isovalent defects (extraneous atoms in the material that substitute for others with the same charge), which could be playing this role. Further investigation is essential to fully grasp the mechanisms behind quantum freezing and melting. □

REFERENCES AND NOTES

1. Z. Xiang *et al.*, *Science* **388**, 736 (2025).
2. E. Wigner, *Phys. Rev.* **46**, 1002 (1934).
3. H. Li *et al.*, *Nature* **597**, 650 (2021).
4. Y.-C. Tsui *et al.*, *Nature* **628**, 287 (2024).
5. B. Spivak, *Phys. Rev. B Condens. Matter* **67**, 125205 (2003).
6. B. Spivak, S. A. Kivelson, *Phys. Rev. B Condens. Matter Mater. Phys.* **70**, 155114 (2004).
7. J. Lorenzana, C. Castellani, C. Di Castro, *Phys. Rev. B Condens. Matter* **64**, 235127 (2001).
8. C. Ortix, J. Lorenzana, C. Di Castro, *Phys. Rev. B Condens. Matter Mater. Phys.* **73**, 245117 (2006).
9. T. Ando, A. B. Fowler, F. Stern, *Rev. Mod. Phys.* **54**, 437 (1982).
10. J. Falson *et al.*, *Nat. Mater.* **21**, 311 (2022).
11. S. Joy, B. Skinner, *Phys. Rev. B* **108**, L241110 (2023).

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[1]National High Magnetic Field Laboratory, Tallahassee, FL, USA.
[2]Department of Physics, Florida State University, Tallahassee, FL, USA.
[3]Department of Physics, Ohio State University, Columbus, OH, USA.
Email: sj24u@fsu.edu; skinner.352@osu.edu

CELL BIOLOGY

A nuclear house divided

Certain fungal plant pathogens maintain varying chromosome distributions across multiple nuclei

Timothy J. Mitchison[1] *and* **William T. Sullivan[2]**

Students learn that a eukaryotic cell contains a single nucleus that encapsulates the genome. Most eukaryotes are diploid, which means that each nucleus contains two sets of chromosomes (2N), one from each parent, before DNA replication occurs, and then twice that amount after this duplication (4N). The nuclei of gametes contain a haploid (1N) genome after segregation and separation of parental chromosomes during meiosis. In fungi, the second meiotic division (meiosis II), which generates haploid gametes, is often followed by a round of ordinary cell division (mitosis) to generate eight haploid ascospores in each fruiting body (an ascus). Nuclei containing fewer than a haploid set of chromosomes likely lack many genes necessary for cell or organism viability. On page 784 of this issue, Xu *et al.* (*1*) report that in two species of fungi, the haploid genome is spread across multiple nuclei, providing striking exceptions to these previously universal concepts.

The functional importance and adaptive benefits of syncytial cells growing with their genome split between different nuclei are not obvious.

Sclerotinia sclerotiorum is an important crop pathogen whose genetics and cell biology are little explored (*2*). *S. sclerotiorum* ascospores contain two nuclei, which is unusual, but not unprecedented, for a eukaryotic cell. For example, human heart muscle cells often contain two diploid nuclei (*3*). However, Xu *et al.* found that each nucleus in an *S. sclerotiorum* ascospore does not contain a whole haploid genome as expected. Rather, the 16 chromosomes are distributed between the two nuclei so that each contains approximately half the genome, with different spores exhibiting distinct, apparently random chromosome combinations in each nucleus (see the figure). This unusual observation is difficult to reconcile with classical genetics and cell biology, yet Xu *et al.* show that *S. sclerotiorum* is not alone in its quirkiness by demonstrating that the genome of *Botrytis cinerea*, another plant fungal pathogen, is also distributed across multiple nuclei. The data of Xu *et al.* prove that the genome is distributed between nuclei in an apparently haphazard way; however, showing that this distribution is truly random would require additional statistics.

Strong evidence is required to invalidate the generality of the "one whole genome per nucleus" rule, and Xu *et al.* accordingly provide documentation and results from rigorous testing. Using fluorescence microscopy and electron microscopy, they demonstrated that each *S. sclerotiorum* ascospore contains two distinct nuclei. Chromosome-specific fluorescent hybridization probes revealed that the entire haploid complement of 16 chromosomes is distributed across the two nuclei in each ascospore. Surprisingly, polymerase chain reaction analysis using chromosome-specific primers revealed that the distribution of chromosomes between the two nuclei is erratic and varies substantially between nuclear pairs in different asco-