SLOW TRAIN TO SCIENCE

FLIP-FLOPPING PHASES

BY KRISTEN COYNE

Physicists love when matter changes phases. It's understandable: Even the most mundane of phase changes — water turning solid at 0 degrees Celsius and gaseous at 100 degrees Celsius — are fascinating when you think about them.

Nature has loads of other phase-changing tricks up its sleeve. They can be driven by temperature, as is the case with H_2O, or other parameters, such as high magnetic fields.

In an experiment published last year involving scientists from the RIKEN Center for Emergent Matter Science, the University of Tokyo in Japan and the High Field Magnet Laboratory (HFML) in the Netherlands, scientists created a material featuring a special two-dimensional gas layer, then subjected it to both high fields and extremely low temperatures. They wanted to see what combinations of field and temperature would prompt that gas to change to a liquid and then a solid. Anytime physicists can provoke a phase transition, they learn a little more about how the world works while gaining knowledge that could one day translate into an advance in electronics, energy or other applications.

What they discovered surprised them. Board this "Slow Train to Science" and check out the stops along the way to learn more.

Science Advisor: Uli Zeitler

Composite fermion liquid to Wigner solid transition in the lowest Landau level of zinc oxide, D. Maryenko et al., *Nature Communications* 9, 4356 (2018).

HOP ON HERE!

1 GROW THE MATERIAL

Before you can study cool behavior, you have to create an environment where you're likely to find it, like a **heterostructure.**

WHAT'S A HETEROSTRUCTURE?

It's what happens when you layer one atomically thin, two-dimensional material over another.

WHAT DID THE SCIENTISTS CREATE?

Atom by atom, they built a thin layer of zinc oxide (ZnO) topped by a thin layer of **magnesium** zinc oxide (MgZnO). Both materials are insulators.

WHY THE MAGNESIUM?

The presence of Mg at the interface between ZnO and MgZnO creates an electric field that traps electrons, resulting in a gas made of freely moving electrons between the two layers, or heterojunction, is what interests the scientists.

REMIND ME ABOUT GASES.

They're a phase of matter (like steam) in which the molecules move around a lot. Liquids have less kinetic energy than gases, and solids have even less kinetic energy than liquids.

WAIT — FREE ELECTRONS IN AN INSULATOR?

The electron gas at the junction of these two insulators is actually a metal!

2 COOL IT DOWN

Using a **cryostat**, scientists lower the temperature around the material so they can slow down the atoms and observe the subtler quantum behaviors inside. It's like looking for a shivering person at a disco: You have to stop the music so the other people quit dancing before you can detect that much more subtle movement. The chillier temps also make the electron gas an even better metal, with the electrons moving more freely.

CRYOSTAT? TRANSLATION, PLEASE!

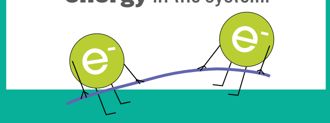
It's a fancy fridge. Instead of Freon, scientists use liquid nitrogen and liquid helium to create extremely cold temperatures. The cryostat extends into the magnet so the material can be really cold while being exposed to high fields.

SO ... THE COLD TURNS THE GAS TO A LIQUID?

Not in this case — this is different than sticking water in the freezer. The purpose of the cold is to "sedate" the atoms. Instead of temperature, scientists will turn up the magnetic field to trigger a phase transition in this electron system.

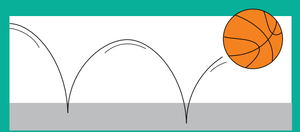
3 TURN ON THE MAGNET

The scientists will gradually increase the field strength over the course of the experiment and observe what happens. The negatively charged electrons in the gas respond to the magnetic field by spinning around it. The higher the field, the faster this cyclotron motion, and the more kinetic energy used by the electrons. So begins a tug-of-war between **kinetic** and **potential energy** in the system.



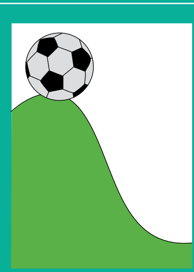
WHAT'S KINETIC ENERGY?

Energy related to motion.



WHAT'S POTENTIAL ENERGY?

Generally, potential energy is the possibility of motion. If you put a ball on top of a hill, it has potential energy because it could roll down. In this case, the potential energy is the repulsion between the electrons, all of which have the same negative charge. If they had more space, they would move further apart.



4 ELECTRONS LIKE EASY STREET

There's no free lunch for electrons. They have to spend energy either moving around, or sitting still on a crystal lattice and overcoming the repulsive force of their neighbors. They default to whichever option requires less energy.

Putting electrons in a magnet increases their kinetic energy. If the field climbs high enough, the kinetic energy required to maintain their gas phase becomes too high, and they hunker down and fall under the influence of potential energy instead. That's when they transition to a liquid or solid.

5 ELECTRONS GET WEIRD

But before this electron gas transitions to another phase, another kind of change occurs. This happens just as the magnetic field reaches a value of about 14 **teslas**: The electrons turn into **composite fermions.**

WHAT'S A TESLA?

A unit of magnetic field strength. A typical hospital MRI magnet is 2 or 3 teslas.

WHAT'S A COMPOSITE FERMION?

As electrons interact with a magnetic field, they can sometimes steal, or pin down, a part of it. In a sense, they become a kind of hybrid particle: a composite fermion.

6 THINGS GET INTERESTING

The magnetic field keeps rising until, at about 16 teslas, two changes abruptly occur: The **resistance** of the electrons plummets to almost zero, and the composite fermion gas condenses briefly into a special kind of liquid called a **Laughlin liquid**.

WHAT'S RESISTANCE?

A measure of how well electricity (electrons) travel through a material. Metals have low resistance, insulators have high resistance.

WHAT IS A LAUGHLIN LIQUID?

Named after Nobel Prize–winning physicist Robert Laughlin, it's a quantum fluid that can form at high fields and low temperatures.

7 LIQUID TO SOLID

The liquid's life is brief. As the magnetic field continues to climb, the liquid transitions into a type of solid called a **Wigner solid**, and the resistance of the system shoots back up. The colder the system, the higher its resistance, i.e., the better an insulator it becomes.

WHAT IS A WIGNER SOLID?

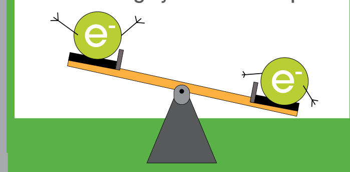
Named after Hungarian-American scientist Eugene Wigner, who first predicted it in 1934, it's a solid-like state that can occur in electrons in a 2D material at a high magnetic field.

8 SOLID TO LIQUID

But as the magnetic field reaches about 17.5 teslas, it's *déjà vu*: The resistance takes another nosedive, and the solid reverts to a liquid.

9 FLIP-FLOPPING PHASES

This strange cycle repeats itself a few more time as the system vacillates between an insulating solid and highly conductive liquid.



TERMINUS

10 THE BIG QUESTION

While the scientists could accurately measure the system's resistance and deduce its states of matter, they can't say for sure whether the Wigner solids they observed were made up of electrons or composite fermions. This is an important question that further experiments and theory work could help answer, said HFML physicist Uli Zeitler, who was part of the research team. Either way, he said, the results are exciting. "The interactions between these electrons are much stronger in this material than in other materials," he said. "This is data that help us to understand interactions between electrons and even to use them [one day] for something useful."