HOP ON HERE!

1. COOK A CRYSTAL

Haravifard begins by designing and synthesizing a **magnetic crystal** – specifically, a type of material called a **frustrated magnet.**

WHAT'S A CRYSTAL?

It's a solid material in which all atoms, molecules and ions are strictly ordered in a lattice with a regular pattern that repeats in all directions.

A crystal is a 3-dimensional structure, but physicists can study what happens in its 2-dimensional layers, where the magnetic behavior occurs.

WHAT MAKES IT MAGNETIC?

You need to include a magnetic ion, such as copper, so that different parts of the crystal interact magnetically.

Magnetic ions spin – kind of like a top – in a specific orientation, either "up" or "down." Physicists call this a "magnetic moment," or just "spin."

HOW CAN A MAGNET BE FRUSTRATED?

It can't settle down into its lowest-energy state ... more on that ahead!

HOW DOES SHE MAKE IT?

Haravifard generally uses a floating zone optical furnace that can reach 3,000°C (5,432°F) and makes very pure crystals. (Because they "float" in the furnace, the crystals don't touch anything and stay pretty pure.)

THE COOL THING ABOUT MAGNETIC CRYSTALS.

Thanks to their magnetic moments, magnetic ions in the crystal interact with each other via their atomic bonds.

2. SHAKE IT UP

Then it's time to shake things up. Haravifard can fiddle with several parameters to influence how the magnetic ions in her crystal interact with each other. You could think of these as arrows in her scientific quiver. The first is **chemical doping.**

SHE MAKES THEM STUPID?

Not at all. She substitutes some magnetic ions in her crystal for a non-magnetic ion (such as magnesium) or for a different magnetic ion with another atomic size.

WHY?

It's like swapping out a family member for a total stranger: The interactions throughout the crystal lattice layer will be affected, resulting in a very different behavior.

3. CHILL OUT

The next parameter is **temperature** – and this is where things get frustrating! Haravifard cools the crystal down to super-cold temperatures – where interesting **quantum behaviors** begin to emerge!

WHY COOL IT?

To remove the thermal energy.

HOW DOES SHE COOL IT?

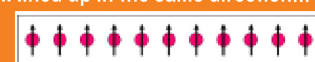
Liquid helium helps her chill the crystal down to close to absolute zero ... −273°C (or −459°F).

THEN WHAT HAPPENS?

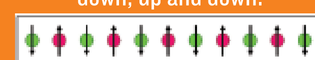
Most materials happily relax into their lowest-energy "ground" state. This means those magnetic moments align in the way that requires the least amount of energy.

WHAT DOES THAT LOOK LIKE?

Generally, that's either ferromagnetic... all lined up in the same direction... or...



... antiferromagnetic, arranged up and down, up and down.



4. SPIN CYCLE

At a certain low temperature, this particular crystal undergoes a **quantum phase transition** ... specifically, it turns into a **spin liquid.**

WHAT'S A PHASE TRANSITION?

When a material changes from one state, or phase, to another – such as from solid ice to liquid water. Phase transitions occur also at the quantum, sub-atomic level (superconductivity is one example).

WHAT'S A SPIN LIQUID?

It's a quantum state of matter that can happen in some materials at very cold temperatures when the spins pair up in a specific way (physicists call this entanglement).

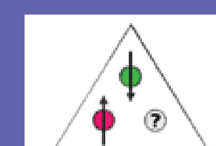
It's not, despite its name, a liquid. But it resembles a liquid in that it's not ordered (whereas solid ice is ordered into neat crystals).

5. ENERGY CRISIS

The spin liquid is awesome! But it still is not ordered. It's still frustrated! The colder it gets, the more it wants to order – and the more frustrated it gets because it can't seem to get rid of that last bit of energy!

WHY CAN'T THEY ORDER?

They can't order because of their geometry. In an antiferrromagnetic system, for example, the lattice might be arranged in triangular configurations that prevent the moments of the magnetic ions from pairing off perfectly into up/down pairs. So two of the three ions will pair off as an up/down duo, but the leftover third ion doesn't know what to do! Should it pair up with the first ion and spin down? Should it pair up with the second ion and spin up? Getting mixed signals, it ends up spinning like a weathervane on a blustery day, preventing the system from ordering.



Need another analogy? Think of a kid confused by conflicting messages. In answer to a question, Dad says, "No," Mom says, "Yes." Which one is it? Frustration, tantrums and other mayhem ensue!

6. APPLY PRESSURE

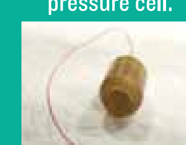
With the material pushed to the brink with frustration, Haravifard pulls out another arrow: high pressure. It's another way to tinker with the crystal. But it remains disordered ... and frustrated!

HOW MUCH PRESSURE?

Up to tens of gigapascals of pressure – several orders of magnitude more than atmospheric pressure.

HOW DOES SHE PRESSURIZE IT?

She puts it inside a specially designed pressure cell.

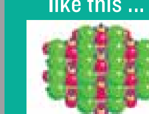


WHAT DOES THIS DO, EXACTLY?

The pressure will physically squeeze the crystal, changing distances and angles between ions in the lattice. That structural change, with any luck, will help bring about a behavioral change in the material.

WHAT'S THAT LOOK LIKE?

It might change from something like this ...



to this ...

7. MAGNET: ON

Now for the pièce de résistance! Time for Haravifard to pull out the final arrow in her quiver: a high magnetic field! This does the trick! Finally, the frustrated, disordered crystal becomes ordered!

HOW DOES THIS HAPPEN?

The magnetic field exerts a torque on the magnetic ions in the crystal, forcing the spins to align into an ordered state.

WHY DOES HARAVIFARD GET SO EXCITED ABOUT THIS?

1.Such experiments can reveal a lot about the physics underlying cool phenomena such as spin liquids, and prompt lots of questions.

2. The more we know, the closer we are to exploiting these transitions for potential use in quantum computers.

3. It's inherently awesome!

WHAT QUESTIONS?

1. What causes exotic states such as spin liquids or superconductivity to emerge from disordered states?

2. Is the transition sudden or gradual?

3. At what magnetic field strength does the transition take place?

4. Is there a relationship between spin liquids and superconductivity?

5. Can we induce a phase transition between the two states in a controlled way, for possible use in quantum computers?

8. SCIENCE SUCCESS!

The knowledge gained from each experiment helps Haravifard refine her recipes for materials with exotic magnetic and electronic states and phase transitions, which she can then use in her continued search for new high-temperature superconductors.

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