PASCAL PUPHAL

Pure LK-99 crystals made at a Max Planck Institute in Stuttgart, Germany.

HOW SCIENCE SLEUTHS SHOWED LK-99 ISN'T A SUPERCONDUCTOR

Efforts to replicate the material explain why it displayed superconducting-like behaviours.

By Dan Garisto

Researchers seem to have solved the puzzle of LK-99. Scientific detective work has unearthed evidence that the material is not a superconductor, and clarified its actual properties.

The conclusion dashes hopes that LK-99 – a compound of copper, lead, phosphorus and oxygen – would prove to be the first superconductor that works at room temperature and ambient pressure. Instead, studies have shown that impurities in the material – in particular, copper sulfide – were responsible for sharp drops in its electrical resistivity and a display of partial levitation over a magnet, properties similar to those exhibited by superconductors.

"I think things are pretty decisively settled at this point," says Inna Vishik, a condensed-matter experimentalist at the University of California, Davis.

The LK-99 saga began in late July, when a team led by Sukbae Lee and Ji-Hoon Kim at the Quantum Energy Research Centre, a start-up firm in Seoul, published preprints[1,2] claiming that LK-99 is a superconductor at normal pressure, and at temperatures up to at least 127 °C (400 kelvin). All previously confirmed superconductors function only at very low temperatures and extreme pressures.

The extraordinary claim quickly grabbed the attention of the science-interested public and researchers, some of whom tried to replicate LK-99. Initial attempts did not find signs of room-temperature superconductivity, but were not conclusive. Now, after dozens of replication efforts, many specialists are confidently saying that the evidence shows LK-99 is not a room-temperature superconductor. (Lee and Kim's team did not respond to *Nature*'s request for comment.)

Accumulating evidence

The South Korean team based its claim on two of LK-99's properties: levitation above a magnet and abrupt drops in resistivity. But separate teams at Peking University[3] and the Chinese Academy of Sciences[4] (CAS), both in Beijing, found mundane explanations for these phenomena.

Another study[5], by researchers in the United States and Europe, combined experimental and theoretical evidence to demonstrate how LK-99's structure made superconductivity infeasible. And other experimenters synthesized and studied pure samples[6] of LK-99, erasing doubts about the material's structure and confirming that it is not a superconductor, but an insulator.

The only further confirmation would come from the South Korean team sharing its samples, says Michael Fuhrer, a physicist at Monash University in Melbourne, Australia. "The burden's on them to convince everybody else," he says.

Perhaps the most striking evidence for LK-99's superconductivity was a video taken by the South Korean team that showed a coin-shaped sample of silvery material wobbling over a magnet. The researchers said that the sample was levitating because of the Meissner effect – a hallmark of superconductivity in which a material expels magnetic fields. Multiple unverified videos of LK-99 levitating subsequently circulated on social media, but none of the researchers who initially tried to replicate the findings observed any levitation.

Half-baked levitation

Several red flags popped out to Derrick VanGennep, a former condensed-matter researcher at Harvard University in Cambridge, Massachusetts, who now works in finance but was intrigued by LK-99. In the video, one edge of the sample seemed to stick to the magnet, and it seemed to be delicately balanced. By contrast, superconductors that levitate over magnets can be spun and even held upside down. "None of those behaviours look like what we see in the LK-99 videos," VanGennep says.

He thought LK-99's properties were more likely to be the result of ferromagnetism. So he constructed a pellet of compressed graphite shavings with iron filings glued to it. A video made by VanGennep shows that his disc – made of non-superconducting, ferromagnetic materials – mimicked LK-99's behaviour.

On 7 August, the Peking University team reported[3] that this "half-levitation" appeared in its own LK-99 samples because of ferromagnetism. "It's exactly like an iron-filing experiment," says team member Yuan Li, a condensed-matter physicist. The pellet experiences a lifting force, but it's not enough for it to levitate – only for it to balance on one end.

Li and his colleagues measured their sample's resistivity, and found no sign of superconductivity. But they couldn't explain the sharp resistivity drop seen by the South Korean team.

Impure samples

The South Korean authors noted one particular temperature at which LK-99 showed a tenfold drop in resistivity, from about 0.02 ohm-centimetres to 0.002 Ω cm. "They were very precise about it: 104.8 °C," says Prashant Jain, a chemist at the University of Illinois at Urbana–Champaign. "I was like, wait a minute, I know this temperature."

The reaction that synthesizes LK-99 is an unbalanced recipe. For every one part that it makes of copper-doped lead phosphate crystal – pure LK-99 – it produces 17 parts copper and 5 parts sulfur. These leftovers lead to numerous impurities – especially copper sulfide (Cu$_2$S), which the South Korean team reported finding in its sample.

Jain, a copper-sulfide specialist, remembered 104 °C as the temperature at which Cu$_2$S undergoes a phase transition. Below that temperature, the resistivity of air-exposed Cu$_2$S drops dramatically – a signal almost identical to LK-99's purported superconducting phase transition. "I was almost in disbelief that they missed it," says Jain, who published a preprint[7] on the important confounding effect.

On 8 August, the CAS team reported[4] on the effects of Cu$_2$S impurities in LK-99. "Different contents of Cu$_2$S can be synthesized using different processes," says team member Jianlin Luo, a CAS physicist. The researchers tested two samples – the first heated in a vacuum, which resulted in 5% Cu$_2$S content, and the second in air, which gave 70% Cu$_2$S content.

The first sample's resistivity increased smoothly as it cooled, as did samples from other replication attempts. But the second sample's resistivity plunged near 112 °C (385 K) – closely matching the South Korean team's observations.

"That was the moment where I said, 'Well, obviously, that's what made them think this was a superconductor,'" says Fuhrer. "The nail in the coffin was this copper sulfide thing."

It is difficult to make conclusive statements about LK-99's properties, because the material is unpredictable and samples contain varying impurities. "Even from our own growth, different batches will be slightly different," says Li. But he argues that samples that are close enough to the original are sufficient for checking whether LK-99 is a superconductor in ambient conditions.

Crystal clear

With strong explanations for the resistivity drop and the half-levitation, many in the community were convinced that LK-99 was not a room-temperature superconductor. But mysteries lingered – namely, what were the material's actual properties?

Initial theoretical attempts using an approach called density functional theory (DFT) to predict LK-99's structure had hinted at interesting electronic signatures known as flat bands. These are areas in which the electrons move slowly and can be strongly correlated. In some cases, this behaviour leads to superconductivity. But these calculations were based on unverified assumptions about LK-99's structure.

To better understand the material, the US–European group[5] performed precision X-ray imaging of its samples to calculate LK-99's structure. Crucially, the imaging allowed the team to make rigorous calculations that clarified the situation of the flat bands, showing that they were not conducive to superconductivity. Instead, the flat bands in LK-99 came from strongly localized electrons, which cannot 'hop' in the way that a superconductor requires.

> **"I was almost in disbelief that they missed it."**

On 14 August, a separate team at the Max Planck Institute for Solid State Research in Stuttgart, Germany, reported[6] synthesizing pure, single crystals of LK-99. Unlike previous synthesis attempts, which had relied on crucibles, this one used a technique called floating-zone crystal growth. This enabled the researchers to avoid introducing sulfur into the reaction, thereby eliminating the Cu$_2$S impurities.

The result was a transparent purple crystal – pure LK-99, or Pb$_{8.8}$Cu$_{1.2}$P$_6$O$_{25}$. Separated from impurities, LK-99 is not a superconductor, but an insulator with a resistance in the millions of ohms – too high for a standard conductivity test to be run. It shows minor ferromagnetism and diamagnetism, but not enough for even partial levitation. "We therefore rule out the presence of superconductivity," the team concluded.

The team suggests that the hints of superconductivity seen in LK-99 were caused by Cu$_2$S impurities, which are absent from their crystal. "This story is exactly showing why we need single crystals," says Pascal Puphal, a specialist in crystal growth and the Max Planck physicist who led the study. "When we have single crystals, we can clearly study the intrinsic properties of a system."

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CAN THE WORLD REALLY STOP WILD POLIO BY THE END OF 2023?

Eradication efforts were described as unsuccessful, so how close are we to eliminating the disease?

By Clare Watson

Afghanistan and Pakistan – the two countries in which polio is still endemic – are closer than they have ever been to eradicating wild poliovirus, the World Health Organization (WHO) said last month. It's a surprising turn, given that the eradication effort had been criticized as floundering as recently as last year. With a small number of cases and limited geographical spread of the virus, scientists agree that the two nations stand a real chance of stopping transmission of wild poliovirus this year, but only if the eradication programmes in these countries can overcome persistent social and political challenges.

"This is the best epidemiological opportunity these two countries have had concurrently" to stop wild poliovirus from circulating, says Hamid Jafari, director of polio eradication at the WHO. With sustained, targeted and coordinated vaccination efforts, "there's now a shared opportunity" for them both to succeed, he adds.

Wiping out wild poliovirus, of which there are three strains, termed serotypes 1, 2 and 3, has been the goal of global eradication efforts since they began in 1988. Types 2 and 3 were successfully eradicated in 2015 and 2019, respectively, but type 1 continues to circulate in Afghanistan and Pakistan 12 years after India quashed all forms of the wild virus, and 7 years after Africa did the same.

An analysis of polio transmission dynamics, published in 2020, found that global eradication efforts were "not on track to succeed" in their goal of eliminating wild poliovirus type 1 by 2023 (D. A. Kalkowska *et al. Risk Anal.* **41**, 248–265; 2021). Fears that eradication was falling out of reach increased again in 2021, when wild poliovirus broke containment lines and emerged in eastern Africa. As recently as February 2023, an article in the *New England Journal of Medicine* suggested eradication of the virus had been "unsuccessful" (K. Chumakov *et al.*