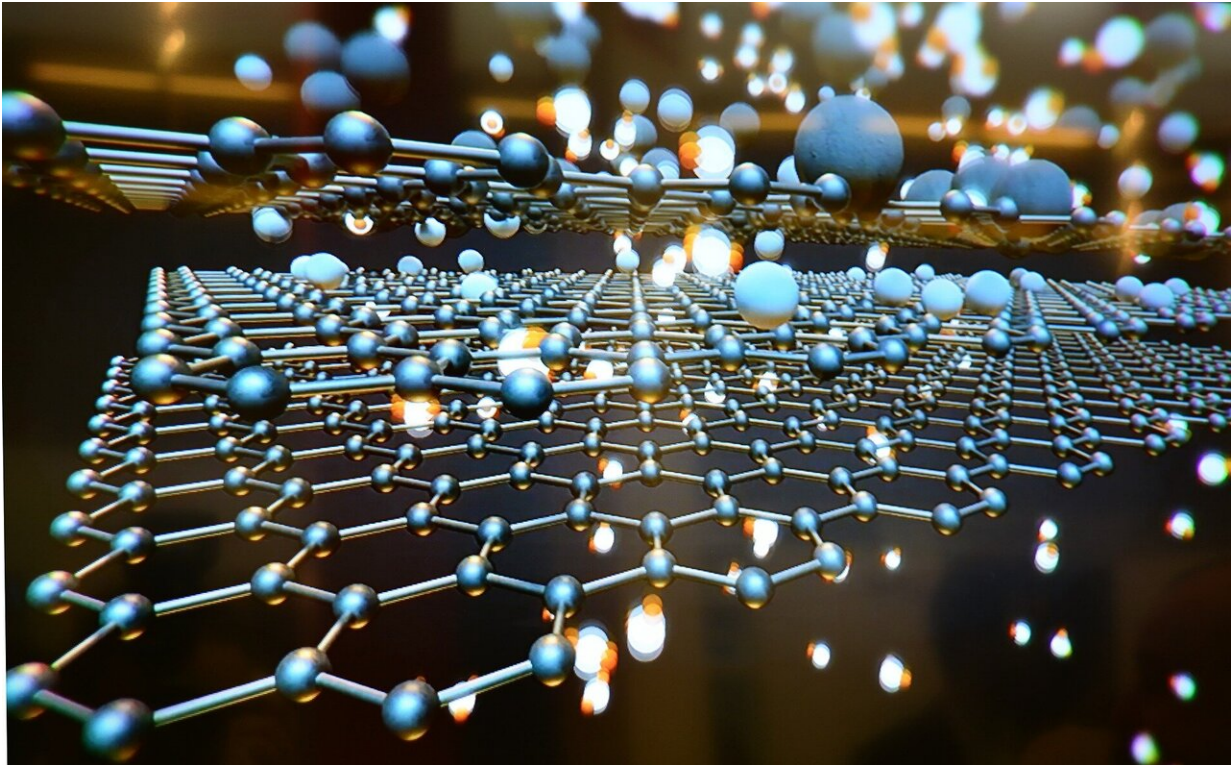


The quest for the magic angle

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Stack two layers of graphene, twisted at slightly different angles to each other, and the material spontaneously becomes a superconductor. Science still can't explain how something so magical can happen, but physicists use special equipment to reveal what is taking place under the surface.

Superconductivity is a subject that has intrigued scientists for generations, since it was first noted more than 100 years ago, in the Leiden laboratory of Nobel Prize winner Heike Kamerlingh Onnes. He cooled mercury to near absolute zero and suddenly, all resistance disappeared. If you introduce an electric current to such a cold metal, it will continue to flow until the cooling is stopped.

Cooling in this case means a temperature of around 270 degrees below zero, the temperature at which helium becomes liquid. This is complicated and expensive, so practical applications of superconductivity were limited to the magnets in MRI scanners in hospitals, up till now.

In the meantime, physicists have been searching for 'warm' superconductors which will operate with less cooling. For example, ceramic materials have been developed which are superconducting at minus 140. That's progress, but we're not there yet. There are still a lot of unanswered questions. What exactly happens inside those materials is one such question to which Leiden researchers Tjerk Benschop and Sense Jan van der Molen hope to find an answer.

"History has taught us that a quest like that can take time," says Van der Molen, professor of Condensed Matter Physics. "Kamerlingh Onnes discovered superconductivity in 1911, but it wasn't until 1957 that a good explanatory theory was published. And we still don't completely understand those new ceramic superconductors. It's complicated, even for physicists. That was also the premise for our collaboration: let's take a relatively simple material to experiment with: [graphene](#)."

Ph.D. candidate Tjerk Benschop: "What's interesting is that the phase transition to superconductivity with graphene is similar to that of the ceramic superconductors. The idea is that by studying graphene, we can learn more about what happens in other superconductors."

New twist

Everyone has graphene in their homes. The graphite core of a pencil consists of endless layers of graphene, in which carbon atoms are neatly arranged in a honeycomb structure. Van der Molen: "Bilayer graphene has particular characteristics: you can literally give it a new twist. If you twist two layers of graphene at a slight angle, you suddenly get a superconducting material. And if you increase the angle between the layers, that phenomenon disappears. There's a lot of complex physics behind that, and in some respects it's still difficult to explain."

Benschop: "It sounds a bit mad, but at a magic angle of 1.1 degrees, electrons in the two layers start to sense each other more; they're able to interact. That results in unique characteristics, one of which is superconductivity. It's difficult to explain why that is the case, because there are many physics-related steps in between. For example, we're talking about bands of electrons, something which is hard to imagine."

Flat bands

An international group of researchers has charted the superconducting graphene sandwich in detail, using a number of measuring techniques. They combined the expertise in the field of superconductivity of Benschop's supervisor, Milan Allan, and colleague Felix Baumberger in Switzerland with Van der Molen's graphene research. "If you measure really accurately, you can even ascertain the condition of the electrons in the material. Until now, no-one had succeeded in demonstrating that electrons are more or less motionless in the magic angle in what is known as a flat band. And it took a huge amount of work."

Benschop: "At one point, I sacrificed my Christmas holiday to make images of twisted graphene. The difficult thing about my technique is

that you can only measure accurately if the surface of the graphene is scrupulously clean. You're scanning with a microscopically small needle above the surface and if there's as much as a single molecule of dirt somewhere, your measurement fails. That caused me a lot of hassle at the beginning, finding out what worked best one step at a time. For an accurate measurement, the surface of the graphene must be really clean, so we measure in an ultra-high vacuum environment, for example. There are fewer particles floating in the measuring room than there are in space."

Eureka moment

The tiny specimens of twisted bilayer graphene were made by fellow physicists in Barcelona, since that's a skill in its own right. "The great thing about science is that you encounter people through publications and conferences and come up with new ideas together," says Van der Molen. "In this case, we needed four research groups to make a success of this."

"After long days in the lab, patiently repeating and improving, there was finally a eureka moment," Benschop tells us. "You spend a long time working towards it, hoping that in the end, you'll be able to get a good measurement. It's such a special moment when you see the atomic structure of the graphene appear on your screen, with that lovely pattern that goes with the correct angle of twist."

As soon as the two layers of graphene are twisted in relation to each other, a large honeycomb structure suddenly becomes visible. It is the same spontaneous pattern-forming or moiré effect that you get when you move two thin layers of silk over each other. Van der Molen: "That pattern isn't just an optical illusion; a new structure actually occurs giving electrons new areas in which to move."

Will there ever be chips with magic-angle graphene in computers or smartphones? Benschop doesn't think so. "Superconductivity occurs in graphene at minus 272 degrees, which makes a practical application infeasible since liquid helium is extremely expensive. Above all, we're learning more and more about how superconductivity occurs and hopefully, this will provide ideas for new materials which are superconducting at room temperature."

Lego

According to Van der Molen, [bilayer graphene](#) is only the beginning. The fact is that there are a lot of other flat, conducting materials which can also be stacked and twisted. "I see it as being like Lego. You put one layer on top of another and if there is strong interaction, a new material with unexpected characteristics occurs. It's a bit like combining hydrogen with oxygen to get water, and where the whole is much greater than the sum of the parts."

Another option Benschop is anxious to research is the warping of bilayer materials since that also changes the moiré patterns and electrical characteristics. "In short, there are a great many parameters with which to experiment," says Van der Molen. "There is a theoretical prediction that the temperature for superconductivity could easily be higher. But how that can be achieved is something we know too little about, as yet. That's also the best part of our professional field: an awful lot of things are difficult to calculate or predict, so experimenting makes the difference."

Provided by Leiden University

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