Molecular graphene heralds new era of 'designer electrons'

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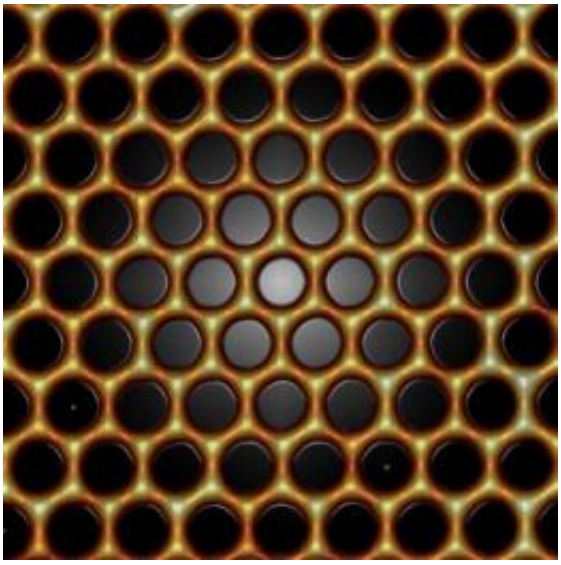
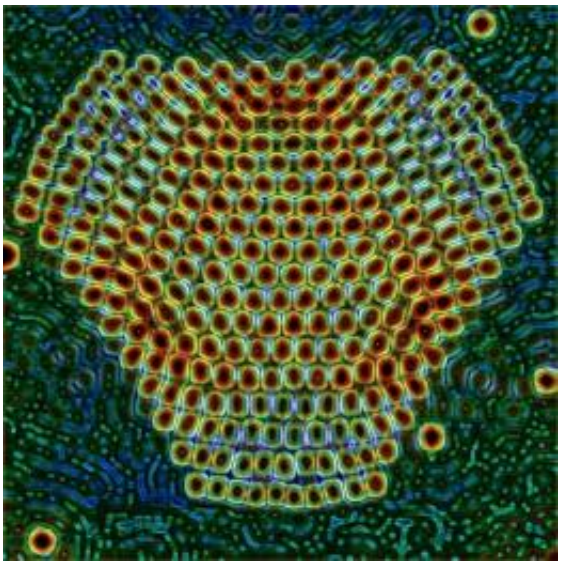


Precisely positioned carbon monoxide molecules (black) guide electrons (yellow-orange) into a nearly perfect honeycomb pattern called molecular graphene. Electrons in this structure have graphene-like properties; for example, unlike ordinary electrons, they have no mass and travel as if they are moving at the speed of light in a vacuum. To make this structure, scientists from Stanford and SLAC National Accelerator Laboratory used a scanning tunneling microscope to move individual carbon monoxide molecules into a hexagonal pattern on a perfectly smooth copper surface. The carbon monoxide repels the free-flowing electrons on the copper surface, forcing them into a graphene-like honeycomb pattern. Credit: Manoharan Lab, Stanford/SLAC

Researchers from Stanford University and SLAC National Accelerator

Laboratory have created the first-ever system of "designer electrons" – exotic variants of ordinary electrons with tunable properties that may ultimately lead to new types of materials and devices.

"The behavior of electrons in materials is at the heart of essentially all of today's technologies," said Hari Manoharan, associate professor of physics at Stanford and a member of SLAC's Stanford Institute for Materials and Energy Sciences, who led the research. "We're now able to tune the fundamental properties of electrons so they behave in ways rarely seen in ordinary materials."

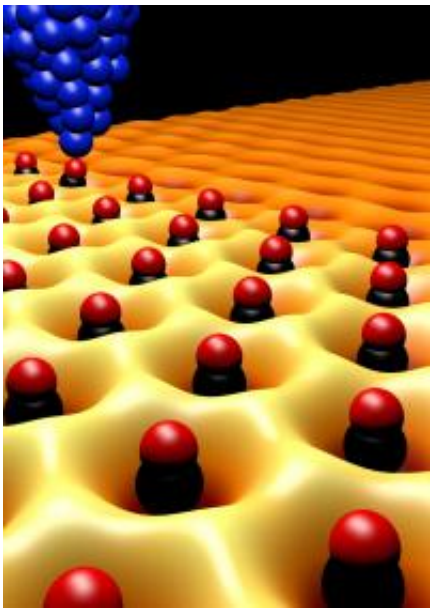


Pictured is a version of molecular graphene in which the electrons are tuned to respond as if they're experiencing a very high magnetic field (red areas) when none is present. Scientists from Stanford and SLAC National Accelerator Laboratory calculated the positions where carbon atoms in graphene should be to make its electrons believe they were being exposed to a magnetic field of 60 Tesla, more than 30 percent higher than the strongest continuous magnetic field ever achieved on Earth (a 1 Tesla magnetic field is about 20,000 times stronger than the Earth's). The researchers then used a scanning tunneling microscope to place carbon monoxide molecules (black circles) at precisely those positions. The electrons responded by behaving exactly as expected -- as if they were

exposed to a real field. Credit: Manoharan Lab, Stanford/SLAC

Their first examples, reported today in *Nature*, were hand-crafted, honeycomb-shaped structures inspired by graphene, a pure form of carbon that has been widely heralded for its potential in future electronics. Initially, the electrons in this structure had graphene-like properties; for example, unlike ordinary electrons, they had no mass and traveled as if they were moving at the speed of light in a vacuum. But researchers were then able to tune these electrons in ways that are difficult to do in real graphene.

To make the structure, which Manoharan calls molecular graphene, the scientists use a scanning tunneling microscope to place individual carbon monoxide molecules on a perfectly smooth copper surface. The carbon monoxide repels the free-flowing electrons on the copper surface and forces them into a honeycomb pattern, where they behave like graphene electrons.



This graphic shows the effect that a specific pattern of carbon monoxide molecules (black/red) has on free-flowing electrons (orange/yellow) atop a copper surface. Ordinarily the electrons behave as simple plane waves (background). But the electrons are repelled by the carbon monoxide molecules, placed here in a hexagonal pattern. This forces the electrons into a honeycomb shape (foreground) mimicking the electronic structure of graphene, a pure form of carbon that has been widely heralded for its potential in future electronics. The molecules are precisely positioned with the tip of a scanning tunneling microscope (dark blue). Image credit: Hari Manoharan / Stanford University.

To tune the electrons' properties, the researchers repositioned the carbon monoxide molecules on the surface; this changed the symmetry of the electron flow. In some configurations, electrons acted as if they had been exposed to a magnetic or electric field. In others, researchers were able to finely tune the density of electrons on the surface by introducing defects or impurities. By writing complex patterns that mimicked changes in carbon-carbon bond lengths and strengths in graphene, the researchers were able to restore the electrons' mass in small, selected areas.

"One of the wildest things we did was to make the electrons think they are in a huge magnetic field when, in fact, no real field had been applied," Manoharan said. Guided by the theory developed by co-author Francisco Guinea of Spain, the Stanford team calculated the positions where carbon atoms in graphene should be to make its electrons believe they were being exposed to magnetic fields ranging from zero to 60 Tesla, more than 30 percent higher than the strongest continuous magnetic field ever achieved on Earth. The researchers then moved carbon monoxide molecules to steer the electrons into precisely those positions, and the electrons responded by behaving exactly as predicted – as if they had been exposed to a real field.

"Our new approach is a powerful new test bed for physics," Manoharan said. "Molecular graphene is just the first in a series of possible designer structures. We expect that our research will ultimately identify new nanoscale materials with useful electronic properties."

Provided by SLAC National Accelerator Laboratory