

Big Bang gravitational effect observed in lab crystal

Phenomenon thought to occur only in exotic, high-energy physics environments seen in quantum material.

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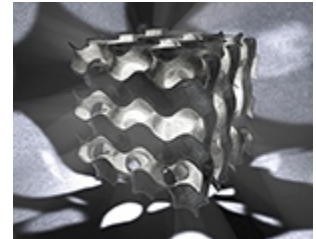
Robert Strasser, Kees Scherer; collage: Michael Bölker

A laboratory crystal can be used to demonstrate how the curvature of space-time might affect Weyl fermions.

An exotic effect in particle physics that's theorized to occur in immense gravitational fields — near a black hole, or in conditions just after the Big Bang — has been seen in a lump of material in a laboratory, physicists report.

A team led by physicist Johannes Gooth at IBM Research near Zurich, Switzerland, say they have seen evidence for a long-predicted effect called the axial-gravitational anomaly¹. It states that huge gravitational fields — which general relativity describes as the result of enormous masses curving space-time — should destroy the symmetry of particular kinds of particles that usually come in mirror-image pairs, creating more of one particle and less of another.

The kinds of conditions needed to prove this unusual breakdown of a fundamental ‘conservation law’ can’t be created in a laboratory. But the researchers exploited a peculiar parallel between gravity and temperature to create a lab analogue of the anomaly in niobium phosphide crystals. “This anomaly is so hard to measure that even indirect evidence is a major breakthrough,” says team member Adolfo Grushin of the University of California, Berkeley.



The strange topology that is reshaping physics

Inside the crystal, the effect is as if a drawerful of pairs of gloves were suddenly to acquire an excess of right-handed gloves because some of the left-handed ones had switched handedness. The result, published in *Nature*², bolsters an emerging view that quantum materials — crystals whose properties are dominated by quantum-mechanical effects — can act as experimental test-beds for physics effects that could only otherwise be seen under exotic circumstances.

Quasiparticles and quantum materials

The particles affected by the anomaly are known as Weyl fermions, which were proposed in the 1920s by mathematician Hermann Weyl. These particles differ from other kinds of fermions (such as the electron) because they seem to have no mass, and because they also have a kind of handedness, or chirality.

Weyl fermions have never been seen as individual physical entities — although it’s thought they might be fleetingly involved in the decays of other kinds of particles. But they have been spotted as ‘quasiparticles’ inside some crystals. In these materials, quantum-mechanical effects cause a material’s electrons to move together in such a way that their collective behaviour resembles that of Weyl fermions. The chiral Weyl fermions are generally produced in equal numbers, like mirror-image pairs.

In 2015, researchers showed that strong magnetic and electric fields could break this symmetry inside a quantum material known as a Dirac semimetal³ — vindicating a long-predicted effect in high-energy physics called the axial (or chiral) anomaly.

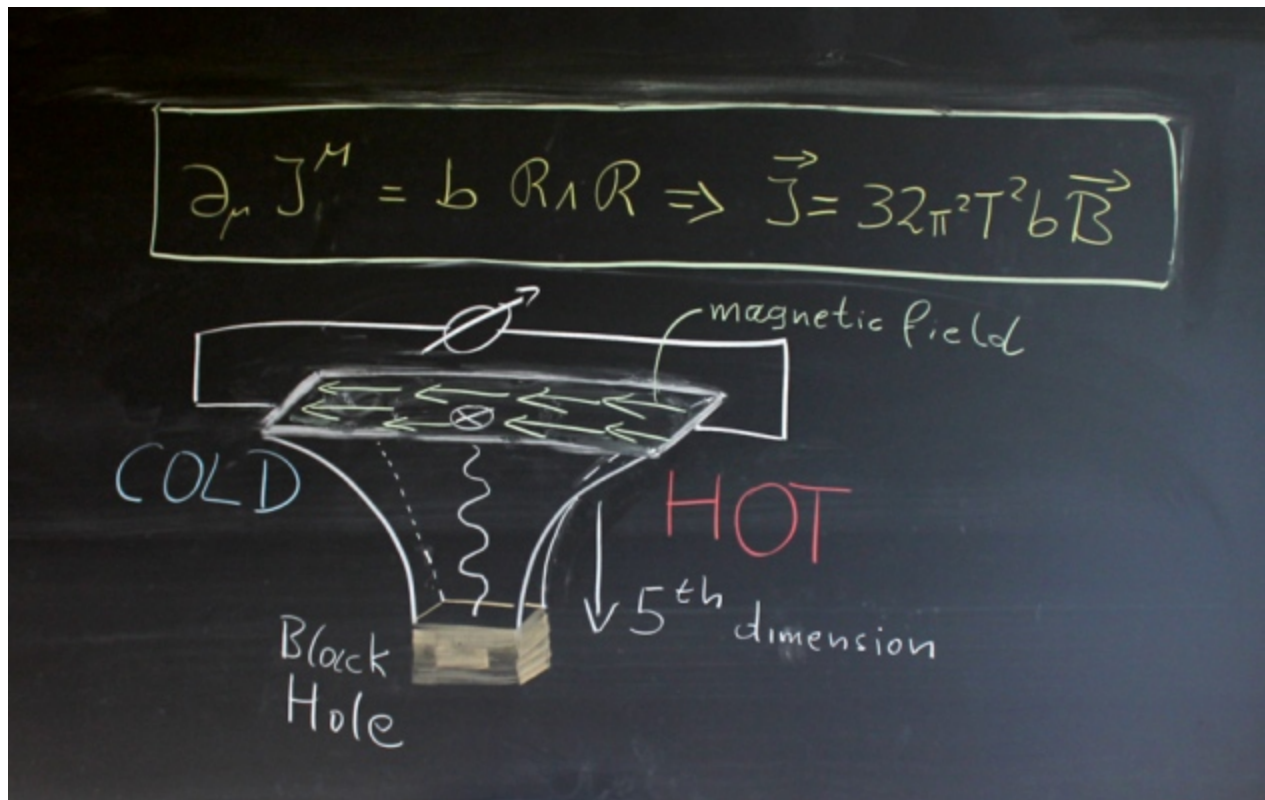


Now, Gooth's team has confirmed that gravity — or space-time curvature — can also destroy the symmetry. To do so, they relied on a connection between gravitational and temperature effects, which states that the effect of space-time curvature on Weyl fermions is mathematically equivalent to the effect of a gradient in temperature^{4, 5}. In other words, the anomaly should also appear if one part of a material in which Weyl fermions appear is hotter than another.

The quantum source of space-time

The reason “is rooted in Einstein's famous equation $E = mc^2$ ”, explains Gooth. “In relativistic quantum field theory, energy and mass flows become the same,” he says. “Mass flow is driven by gravitational-field gradients, and energy flow by temperature gradients. The temperature gradient for the relativistic Weyl fermions thus mimics a gravitational-field gradient.”

The researchers measured the conductivity of their crystalline niobium phosphide — which is known as a Weyl semimetal — in a microelectronic circuit. When they applied a thermal gradient and a magnetic field, they saw an induced electric current created by an imbalance in the two types of Weyl fermion: the number of left-handed quasiparticles moving in one direction through the sample was not the same as the number of right-handed ones moving in the opposite direction. Furthermore, “the behaviour of the current as we change the magnetic field is exactly what the theory of the axial-gravitational anomaly predicts”, says Grushin.



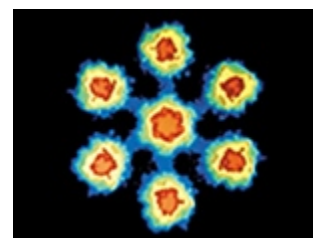
Karl Landsteiner

A chalkboard sketch shows how applying a temperature gradient to certain type of quantum material can mimic the conditions near a black hole.

Compelling evidence

Not everyone is persuaded that the researchers have observed what they claim. Boris Spivak, a physicist at the University of Washington in Seattle, insists that the axial-gravitational anomaly simply doesn't exist in Weyl semimetals. A temperature gradient, he says, can't induce electrons to convert between the two quasiparticles of different handedness. "There are many other mechanisms which can explain their data," Spivak says. He thinks the researchers are just measuring the impact of a magnetic field on the well-known thermoelectric effect, in which electrical currents are produced by temperature gradients.

But Gooth and his colleagues disagree. They say that the existence of the temperature-induced chiral anomaly is strongly supported by theory. And Subir Sachdev, a specialist on quantum effects in solid-state materials at Harvard University in Cambridge, Massachusetts, says the researchers have "compelling evidence for the physical consequences of the axial-gravitational anomaly".



Fire up the atom forge

The existence of the anomaly was not really in doubt, Sachdev adds, but “it is nice to see it appear in real materials”. He says it confirms that gravity interacts with quantum fields in the manner indicated by Einstein’s theories of relativity.

Grushin suspects that understanding how this anomaly manifests in these materials should lead to new physics. And IBM also hopes that the finding might be exploited in electronics, because it generates an electrical current inside the niobium phosphide crystal. Devices that exploit the anomaly might improve the efficiency of materials that can generate electrical energy from temperature gradients, Gooth says.

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