Black holes: a model for superconductors?

March 2 2011

This artist's concept shows a galaxy with a supermassive black hole at its core. The black hole is shooting out jets of radio waves. Image credit: NASA/JPL-Caltech

Black holes are some of the heaviest objects in the universe. Electrons are some of the lightest. Now physicists at the University of Illinois at Urbana-Champaign have shown how charged black holes can be used to model the behavior of interacting electrons in unconventional superconductors.

"The context of this problem is high-temperature superconductivity," said Phillips. "One of the great unsolved problems in physics is the origin of superconductivity (a conducting state with zero resistance) in the copper oxide ceramics discovered in 1986." The results of research by Phillips and his colleagues Robert G. Leigh, Mohammad Edalati, and Ka Wai Lo were published online in *Physical Review Letters* on March 1 and in *Physical Review D* on February 25.

Unlike the old superconductors, which were all metals, the new superconductors start off their lives as insulators. In the insulating state of the copper-oxide materials, there are plenty of places for the electrons to hop but nonetheless—no current flows. Such a state of matter, known as a Mott insulator after the pioneering work of Sir Neville Mott, arises from the strong repulsions between the electrons. Although this much is agreed upon, much of the physics of Mott insulators remains unsolved, because there is no exact solution to the Mott problem that is directly applicable to the copper-oxide materials.

Enter string theory—an evolving theoretical effort that seeks to describe the known fundamental forces of nature, including gravity, and their interactions with matter in a single, mathematically complete system.

Fourteen years ago, a string theorist, Juan Maldacena, conjectured that some strongly interacting quantum mechanical systems could be modeled by classical gravity in a spacetime having constant negative curvature. The charges in the quantum system are replaced by a charged black hole in the curved spacetime, thereby wedding the geometry of spacetime with quantum mechanics.

Since the Mott problem is an example of strongly interacting particles, Phillips and colleagues asked the question: "Is it possible to devise a theory of gravity that mimics a Mott insulator?" Indeed it is, as they have shown.

The researchers built on Maldacena's mapping and devised a model for electrons moving in a curved spacetime in the presence of a charged black hole that captures two of the striking features of the normal state of high-temperature superconductors: 1) the presence of a barrier for electron motion in the Mott state, and 2) the strange metal regime in which the electrical resistivity scales as a linear function of temperature, as opposed to the quadratic dependence exhibited by standard metals.

The treatment advanced in the paper published in Physical Review Letters shows surprisingly that the boundary of the spacetime consisting of a charged black hole and weakly interacting electrons exhibits a barrier for electrons moving in that region, just as in the Mott state. This work represents the first time the Mott problem has been solved (essentially exactly) in a two-dimensional system, the relevant dimension for the high-temperature superconductors.

"The next big question that we must address," said Phillips, "is how does superconductivity emerge from the gravity theory of a Mott insulator?"

Provided by University of Illinois College of Engineering