quick study

From black holes to strange metals

Hong Liu

String theory relates gravity to the physics of a novel phase of matter observed above the superconducting transition temperature.

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Ever since the end of the Stone Age, metals have fascinated humankind and have been vital in the development of civilization. More recently, physicists have been fascinated by a new class of "strange" metals, discovered two decades ago, whose exotic properties challenge fundamental notions of condensed-matter physics. In this Quick Study I describe how a string-theory concept called holographic duality has been applied to shed light on some of the mysteries of that novel metallic state.

Strange metals

At first blush, metals sound simple: They are collections of mobile electrons interacting with one another via the Coulomb potential. In fact, a metal is a complicated, interacting many-body system for which no exact theoretical treatment exists. In his Fermi liquid theory, Lev Landau argued that the fermionic nature of electrons—they obey the Pauli exclusion principle—significantly constrains possible low-energy dynamics. The metal, he reasoned, behaves like a gas of almost noninteracting fermionic "quasiparticles" that may be thought of as electrons suitably modified by dint of their interactions. The quasiparticles have the same charge and spin as the electron, but other properties, including mass and magnetic moment, are altered. Metals are good conductors of electricity and heat because the quasiparticles can move around freely, only rarely scattering off one another.

The Fermi liquid theory has been remarkably successful: Until the discovery of strange metals, it was capable of describing all metallic states in nature. The presence of quasiparticles, their fermionic nature, and their low scattering rate have been confirmed with photoemission experiments that probe a system by removing an electron and watching how the remaining hole interacts with the rest of the system.

Below a certain transition temperature, a metal's resistivity completely vanishes; it becomes a superconductor. Heike Kamerlingh Onnes first discovered the phenomenon a century ago (see the article by Dirk van Delft and Peter Kes, PHYSICS TODAY, September 2010, page 38). For ordinary metals, whose transition temperatures are below 30 K, the physical mechanism underlying the transition has been well understood since the late 1950s. But in 1986 Georg Bednorz and Alex Müller discovered so-called high-temperature superconductors. Those copper oxide compounds, usually referred to as cuprates, have much higher transition temperatures than ordinary metals—as high as 165 K. Theorists have proposed many ingenious ways to understand the physical origin of superconductivity in cuprates and their high transition temperatures, but no consensus has been reached and many mysteries remain.

One of the most significant mysteries is the nature of a phase just above the transition temperature. It has thermodynamic and transport properties significantly different from those of an ordinary metal, prompting the name "strange metal" (see panel a of the figure). Strange metals conduct electricity and heat, as ordinary metals do, but photoemission experiments fail to reveal any particle-like excitations. Electronic interactions in the strange metal are so strong that if you add an electron to the system, it will be devoured before it can propagate far enough to show its particle-like properties. In other words, the electrons that make up a strange metal appear to lose their individuality due to mutual interactions. Such strongly interacting systems might be picturesquely dubbed quantum electron soups (for more on strongly interacting quantum systems, see the special issue of PHYSICS TODAY, May 2010).

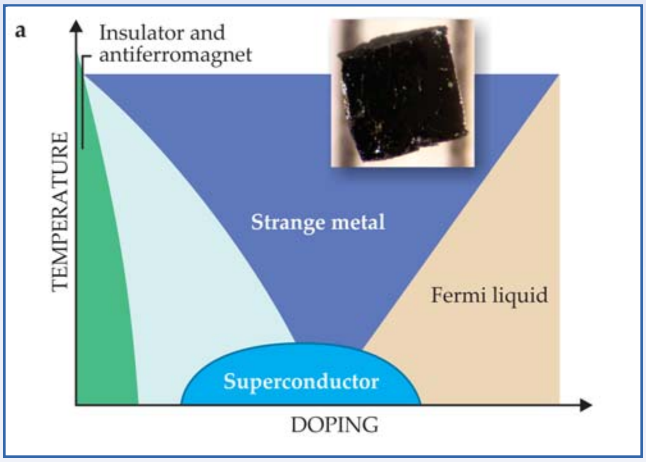
A strange metal cannot be viewed as a gas of charged quasiparticles: How, then, does it conduct electricity and heat? A closely related puzzle is that its resistivity varies linearly with temperature, in contrast with the quadratic temperature dependence of an ordinary metal. After the discovery of that exotic phase in the cuprates, strange-metal behavior was also observed for ordinary metals at the brink of instability—for example, near a phase transition that can occur at zero temperature in response to the tuning of a parameter such as pressure or magnetic field.

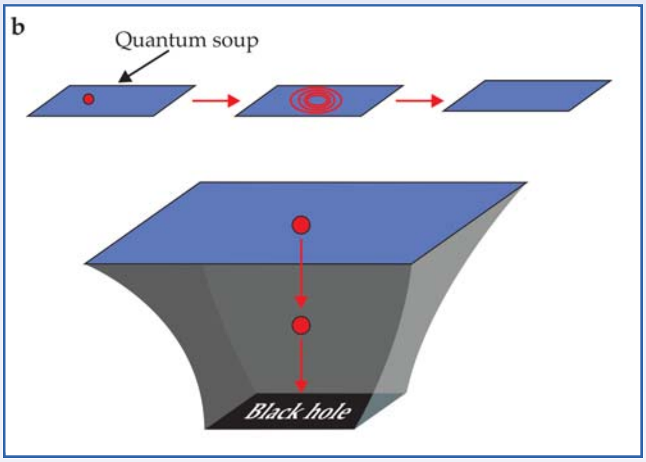
Its many accomplishments notwithstanding, the Fermi liquid theory clearly fails for strange metals. But during the past 15 years, new ideas and methods for approaching strongly interacting quantum systems have come from unexpected directions.

Quantum matter through a gravitational lens

Beginning with a seminal 1997 paper by Juan Maldacena, string theorists have found that certain systems of quantum matter without gravity are equivalent to quantum gravitational systems in a curved spacetime with one additional space dimension. The equivalence goes under the names of holographic duality, AdS/CFT (anti–de Sitter/conformal field theory) correspondence, and gauge–gravity duality (see the article by Igor Klebanov and Maldacena, PHYSICS TODAY, January 2009, page 28). The word "holographic" highlights the difference in spacetime dimensions on the two sides of the equivalence, in analogy to an optical hologram—a two-dimensional representation of a three-dimensional object. I will refer to the lower-dimensional, gravity-free systems as holographic quantum matter.

Remarkably, strongly interacting holographic quantum matter corresponds, in the dual system, to a classical gravitational system, albeit one that usually includes a black hole (see panel b of the figure). Difficult many-body problems that had eluded traditional methods can be mapped to problems





Quantum soup for you! (a) A cuprate such as the bismuth strontium calcium copper oxide sample shown in the inset can exist in a number of phases, depending on its temperature and number of impurities, or doping. At moderate doping and temperatures above the superconducting transition, the cuprate is a strange metal, a strongly interacting system that can be visualized as a quantum electron soup. **(b)** The principle of holographic duality relates the physics of a quantum soup to the gravitational field of a black hole in one higher space dimension. In the upper sequence, a particle (red) added to a quantum soup is rapidly devoured by the system. In the gravity dual, the particle falls into a black hole so rapidly that it barely moves in the transverse directions parallel to the blue boundary.

in classical gravity that are often solvable, sometimes with undergraduate-level methods, in the framework of Einstein's general relativity. Entropy, free energy, and other thermodynamic quantities of the strongly coupled system that would otherwise have been impossible to calculate can often be read directly from the black hole metric that defines the geometry of the higher-dimensional spacetime. Furthermore, the black hole geometry is simple and universal; generically, it is fully specified by the mass, charge, and angular momentum of the black hole. That universality in geometry leads to new universality classes of quantum matter. That is, microscopically different systems that are associated with the same black hole geometry exhibit similar macroscopic behavior. Moreover, simple geometric features of black holes often translate into nonintuitive, strong-coupling phenomena of holographic quantum matter. Thus holographic duality provides powerful tools for discovering new physics.

Semilocal quantum liquids

Nature does not give free passes. The interacting many-electron systems underlying ordinary and strange metals do not yet have a gravity description, and thus the powerful tools offered by the duality cannot be directly applied to them. In fact, at a microscopic level, holographic quantum matter systems associated with known gravity descriptions look nothing like real-life many-electron systems. Nevertheless, one can ask whether, macroscopically, they behave like ordinary metals, strange metals, or something else.

To answer the question, imagine adding a charged fermion to holographic quantum matter with a nonzero charge density. The interaction of that probe with the system corresponds, on the gravity side, to a charged fermionic particle (that is, one satisfying the Dirac equation) propagating in the geometry of a charged black hole. The way in which the fermion scatters off the black hole determines the interaction of the probe with the holographic quantum system. More explicitly, the scattering rate, which describes the probe–system interaction, and the system's resistivity both have the same power-law dependence on temperature, $T^{2\nu}$, with ν a constant. For ordinary metals, the temperature dependence is quadratic; thus $\nu = 1$. For strange metals the temperature dependence is linear; thus $\nu = ½$. For holographic quantum matter, $1 \geq \nu > 0$, a range that encompasses both ordinary and strange metals; the specific value of ν depends on the charge and mass of the particle moving in the black hole geometry. Systems with $\nu > ½$ appear to have weakly interacting quasiparticles as in ordinary metals, whereas systems with $\nu \leq ½$ behave as a quantum electron soup with no particle-like excitations. Intriguingly, the $\nu = ½$ strange-metal behavior seen in cuprates lies precisely at the boundary of the two regimes. A priori, however, holographic techniques do not indicate that $\nu = ½$ should correspond to a real-world material.

A community of physicists is exploring various properties and forms of holographic strange metals, including the possibility that they are examples of a universal intermediate-energy phase. That phase, which Nabil Iqbal, Márk Mezei, and I call a semilocal quantum liquid, has interesting and unusual characteristics. Loosely speaking, properties in a given spatial region of the liquid correlate only with those of regions a finite distance away, but those correlations are maintained indefinitely. A semilocal quantum liquid exists only for a restricted range of temperatures, just like the liquid phase of water. As it cools, it can transition into a variety of other phases, including a superconductor, a Fermi liquid, and an antiferromagnet. Conversely, holographic quantum systems that are vastly different at zero temperature can all transition to a semilocal quantum liquid when warmed; in that sense, the semilocal quantum liquid is a universal phase.

Physicists often make progress by modeling a complicated system in terms of a simple, solvable reference system that captures the essential physics. For strange metals, the appropriate simple reference system has been hard to come by. Maybe the black hole is what we have been looking for.

Additional resource

▶ N. Iqbal, H. Liu, M. Mezei, "Lectures on holographic non-Fermi liquids and quantum phase transitions," http://arxiv.org/abs/1110.3814. ■