Press Release: Observation of a Critical Charge Mode in a Strange Metal

Early pioneers of flight, Otto Lilienthal and the Wright brothers were famously inspired by their careful study of birds to develop the wings for the first airplanes. Today in their quest for new kinds of quantum technology, scientists are once again turning to nature, seeking to gain clues as to how the forces of quantum mechanics give rise to the exotic material properties needed for new devices. Such "quantum materials" include high temperature superconductors that lose their resistivity at liquid nitrogen temperatures, "topological" insulators that are insulating on the inside, but conducting on the outside and "strange metals": so called because of the very unusual way they conduct electricity.

Resistance is a staple property of metals: to send current through a wire requires an applied voltage. In conventional metals, such as iron, copper or gold, resistance derives from electrons dissipating their kinetic energy into heat by scattering off atomic vibrations. The resulting resistivity follows a rather complex dependence on temperature. By contrast the resistance of strange metals is simple: it depends linearly on temperature over a wide temperature range. Remarkably, the rate at which this occurs involves just temperature and two fundamental constants, those of Planck and Boltzmann. Physicists have coined the term "Planckian dissipation" to describe this simple and apparently fundamental electron-scattering behavior in strange metals.

The established theory of metals is based on the idea that electrons move independently. This idea was first proposed by the physicist Paul Drude more than a hundred years ago, and it has stood the test of time. However in strange metals, the dissipation derives from the scattering of electrons off one-another. In fact, Planckian scattering provides the maximum possible rate of dissipation allowed by quantum mechanics, so the old and time-tested ways of treating electricity as a flow of independent electrons has to be set aside.

Strange metals are of particular interest because they have a predisposition on cooling, to transform into superconductors, so that paradoxically, a metal with a very strong rate of dissipation, has a tendency to slip into a low temperature state with zero dissipation. Indeed, strange metal behavior has been seen in a wide variety of unusual superconductors – from high temperature superconductors to twisted layers of graphene. This tantalizing connection has made understanding strange metals a cause celebre, drawing physicists from many different disciplines. Indeed, theoretical methods from the study of string theory and black holes; state-of-the art computational methods using quantum information theory have all been brought to bear on the strange metal problem. Meanwhile, experimental physicists have devised new ways to probe the electrons inside strange metals, exposing them to different kinds of radiation and developing new kinds of microscope.

One of the open questions in strange metals, concerns their charge dynamics. Metals and insulators display quite different patterns of charge fluctuation: in metals, the motion of electrons in and out of atoms, causes them to fluctuate rapidly between different ionic configurations, but in insulators these charge fluctuations are frozen. Thus in iron, the iron atoms fluctuate rapidly between different two ionic configurations Fe^{2+} and Fe^{3+}, but in iron oxide, or "rust", insulating behavior causes the iron atoms freeze into one or the other ionic configurations. One of the most sensitive probes of this behavior is Mossbauer spectroscopy, which uses the nucleus to provide a kind of "time-lapse" photograph of the electric charge surrounding it. In rust, Mossbauer spectroscopy sees the presence of two distinct ionic configurations, but in metal, Mossbauer spectroscopy is too slow to see the valence fluctuations, showing instead a single, average valence of 2.5. This raises the interesting question – what would happen in a strange metal?

To answer this question, a collaboration of physicists from the Institute of Physics, University of Tokyo, University of Hyogo Japan and Rutgers, Johns Hopkins and Cincinatti Universities in the United States have carried out the first Mossbauer study of a strange metal. As the subject of their study, they carefully chose an $YbAlB_4$ an Ytterbium compound commonly referred to as "Y-ball", which exhibits the classic linear resistivity of a strange metal behavior, becoming a superconductor at very low temperatures. In Y-ball, the electrons hop on and off the ytterbium ions, causing them to exist in two valence states Yb^{3+} and Yb^{2+}. Y-ball has the special property that it its strange metal behavior can be switched off by the application of pressure, allowing the physicists to contrast the Mossbauer spectrum of a strange and conventional metal.

Mossbauer spectroscopy uses small shifts in nuclear energy levels, measured by X-ray or gamma ray absorption, to detect changes in the valence of the ion. Traditional Mossbauer methods use radioactive isotopes for this purpose, but in their experiment scientists used a synchrotron, Spring-8 in Japan, to bypass the use of radioactive isotopes and generate a much stronger signal. In their experiment, the synchrotron provides a pulse of high-energy X-rays to excite nuclei in a reference sample of Ytterbium into excited states that a short-while later, emits X-rays of the appropriate wavelength to measure the Mossbauer absorption spectrum of Y-ball.

When the team measured the Mossbauer spectrum of Y-ball they found that as the sample is cooled into the region of strange metal behavior, the Mossbauer spectrum broadens into a double peak, associated with the development of slow valence fluctuations between the Yb^{3+} and Yb^{2+} configurations as part of the strange metal. Remarkably, when pressure is applied to transform the Y-ball from strange metal into a conventional metal, the double peaked Mossbauer spectrum reverted to a single line. In this way they could prove that the strange metal state is associated with very slow or "critical" valence fluctuations between the Yb^{3+} and Yb^{2+} ions. The measured lifetime of the valence fluctuations in the strange metal was found to be about one fluctuation per nano-second.

On the scale of quantum mechanics, a nano-second is an eternity. When the team compared the measured rate of charge fluctuations with the Planckian dissipation rate, they found it was a thousand times slower. In fact, the team realized that at low temperatures, even the Planckian time scale would have been slow enough to allow the atoms to recoil after each valence fluctuation of the Yb ions in Y-ball, causing a further slow down in the critical charge fluctuations and a reduction in the Mossbauer absorption intensity. From the temperature dependence of this intensity, they were able to confirm this reduction intensity, providing indirect evidence that slow valence fluctuations of the strange metal are accompanied by a lattice motion.

One of the important aspects of this work, is that an interdisciplinary methodology has helped shed new light on strange metals. While it is not yet known whether the unusually slow charge fluctuations of Y-ball are a universal property of all strange metals, it is a pretty exciting hypothesis and one that can be tested by extending the synchrotron Mossbauer method to other materials. Meanwhile the march to understand these new metals has an important new clue on the road to harnessing the strange metallic state for future quantum technologies.