PHYSICS

Watching Electrons Break Up

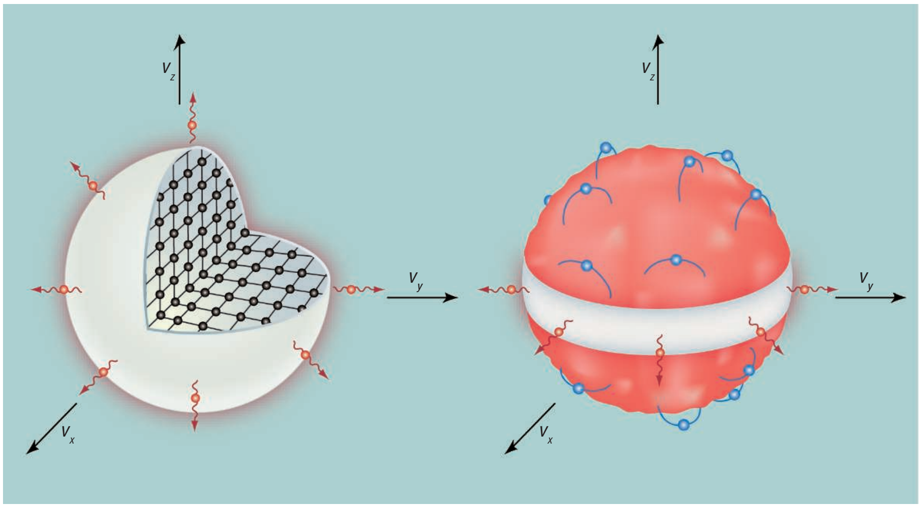
A basic relation between heat and charge transport in metals is violated in some materials, which may offer insights into the high-temperature cuprate superconductors.

Piers Coleman

Electrons are surprisingly rugged particles that fiercely maintain their identity in metals. As they move, they conduct heat and electric charge in all directions in a precisely fixed ratio, a universal property of electricity called the Wiedemann-Franz law. On page 1320 of this issue, Tanatar *et al.* (*1*) show that under the right conditions, metals can exhibit a new type of electrical conductivity for which the Wiedemann-Franz law no longer holds. Under these conditions, conventional electrons appear to live alongside a fundamentally different kind of electricity in which electrons have broken apart and reformed into a new class of charge- and heat-carrying excitation. Such failures of accepted laws in science often signal new and interesting underlying causes, and these results may help us understand the mechanisms behind high-temperature superconductors and other unusual materials.

In the 19th century, physicists empirically discovered two important laws governing the thermal and electrical properties of dense matter: the Dulong-Petit law and the Wiedemann-Franz law. At that time, most scientists believed that Dulong and Petit's law, stating that the specific heat of all materials is a constant, was a fundamental law of nature. Yet it was the failure of the Dulong-Petit law at low temperatures in the 20th century that helped to usher in the era of quantum mechanics (*2*). Early on, physicists did not understand the mechanisms behind the Wiedemann-Franz law, yet it went on to survive, and we know it now to be a consequence of the discrete, quantum nature of electrons in electrical current.

In a normal metal, the quantum motion of electrons is very highly organized (see the left panel of the figure) and might be likened to the organization of aircraft traffic near a major airport. Just as airplanes are stacked by altitude, each in its own slot, electrons are tightly stacked in velocity up to a maximum value called the Fermi velocity. Electron traffic is controlled by quantum physics and the "Pauli exclusion principle," which prevents more than two electrons per velocity slot and helps electrons protect their identity, even as they jostle one another inside the electron cloud. As long as this organization holds, the Wiedemann-Franz law is expected to remain intact.



Electron flight patterns. (**Left**) Electrons in a conventional metal form a tightly organized swarm, in which each electron moves in its own specific velocity slot, filling each available slot up to a maximum level called the Fermi velocity. Excitations at the surface of this "Fermi sphere" carry heat and charge in a fixed universal ratio, in all directions. (**Right**) In $CeCoIn_5$, well-defined electrons transport heat and charge in the *x-y* velocity plane, but transport in the *z* direction is far more turbulent. In these directions, electrons break up into new and as-yet-unidentified types of excitation that carry heat and charge in a different ratio from conventional electricity.

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Today, physicists are seeking new ways to reorganize and control the motions of electrons inside dense matter and profoundly change their properties. One of the ideas being explored is to try reorganizing electrons by increasing the strength of quantum fluctuations. These fluctuations are rooted in Heisenberg's uncertainty principle, which states that certain variables (such as energy and time, or position and momentum) can vary statistically as long as the product of the variations is constant. Thus, tightening the range of fluctuation in one variable will increase the fluctuations in another. Such fluctuations can be enhanced by tuning a metal to the brink of instability (via changes in temperature, composition, or applied fields), where it sits between one stable phase and another. Such a point of instability is called a quantum critical point (*3*–*5*), where the quantum fluctuations engulf the entire material. When this happens in a metal, the physics of the metal is found to change profoundly (*6*, *7*).

Tanatar *et al.* investigated whether electrons survive as well-defined particles in a metal that is tuned to such a quantum critical point, and to do so, they turned to the Wiedemann-Franz law. The material they chose to study is the metal $CeCoIn_5$ (*8*), which can be fine-tuned to a quantum phase transition by applying high magnetic fields (*9*). $CeCoIn_5$ is a layered "heavy fermion" metal in which the electron fluid is delicate and highly prone to instability. At low temperatures, $CeCoIn_5$ is a superconductor (*10*). When a magnetic field is applied, this material becomes a metal again, and just as it does so, it passes through a quantum critical point (*9*).

Tanatar *et al.* measured the heat and charge conductivity in different directions as the metal passes through this critical point. At high fields they found that the material becomes a conventional metal, and the Wiedemann-Franz law is obeyed in all directions. But as the field is lowered, the temperature dependence of the resistance in this material changes profoundly, indicating that something has profoundly changed in the material. When they tuned the material to the quantum critical point, they found no change to the Wiedemann-Franz law when current flows parallel to the layers, but in directions perpendicular to the layers, the Wiedemann-Franz law was consistently found to be violated. By arranging conditions so the material

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approaches the quantum critical point, Tanatar *et al.* could literally "turn off" the Wiedemann-Franz law.

This failure of the Wiedemann-Franz law indicates a severe departure from our standard model of electricity at a quantum critical point. What is going on? Tanatar *et al.* propose an explanation inspired by high-temperature superconductors, in which x-ray measurements show that a continuous Fermi surface breaks up contiguous regions, separated by dead zones where well-defined electrons cease to exist (*10*). Tanatar *et al.* propose that at the quantum critical point, the Fermi surface of CeCoIn$_5$ breaks up into an annulus (see the right panel of the figure), supporting conventional charge and heat transport parallel to the planes of the crystal. But we still do not know what replaces the electron in the directions where the Wiedemann-Franz law fails.

It has taken more than 100 years to find a chink in the armor of the Wiedemann-Franz law, and this new discovery may herald a new understanding of how electricity can transform itself under extreme conditions. Some have suggested that in the fluctuating environment of quantum criticality, the electron actually breaks up into different components (*5*, *11*); it may even break up into separate spin and charge excitations (*12*, *13*). The idea that the electrons may break up into two different groups has also been advanced (*14*), but it is fair to say that no one anticipated this fascinating anisotropic separation into two components. Tanatar *et al.* can rule out some of these scenarios, but certainly not all. What is clear, however, is that at the quantum critical point, a new kind of electricity takes over, and we are only just beginning to understand its properties.

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IMMUNOLOGY

The Cutting Edge of T Cell Selection

The selection of T cells requires their exposure to a repertoire of peptides generated by an organelle whose structure is thymus-specific.

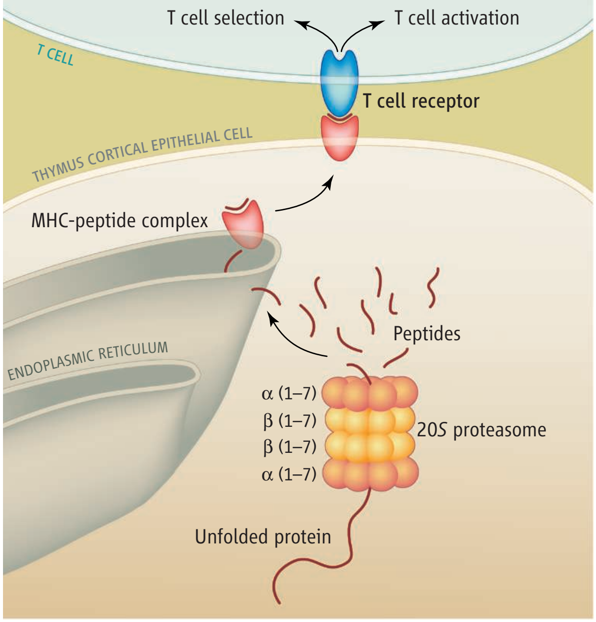
Michael J. Bevan

Why should a single cell type in a single organ of the body express a unique enzymatic component of a protein structure that is ubiquitously expressed? This is the puzzle posed by the study of Murata *et al.* on page 1349 of this issue (*1*), which shows that specific cells in the mouse thymus incorporate a distinct enzyme into their 20*S* proteasomes, the multicatalytic machine that degrades intracellular proteins to peptides. The answer to the puzzle lies in the special role played by these thymic cells in immune system development—that is, determining which immature T cells are selected to survive and populate peripheral lymphoid organs (spleen and lymph nodes), where they survey for unwanted pathogens and tumor cells.

The 20*S* proteasome is a barrel-shaped organelle composed of 14 different proteins in four stacks in the arrangement α(1–7)β(1–7)β(1–7)α(1–7) (see the figure). Misfolded polypeptides in the cell interior are fed into the central bore of the proteasome, where three proteolytic components (β1, β2, and β5) cut them to pieces. The peptides pass out of the proteasome and transit into the endoplasmic reticulum, where a subset binds to the groove of nascent molecules called major histocompatibility (MHC) class I. The MHC-peptide complex folds into a mature structure that is transported to the cell surface, where the MHC molecule "presents" the peptide extracellularly. This process happens in all vertebrate cells, and in humans it is the means by which specific T cells (CD8$^+$ subtype) detect foreign antigens such as those encoded by a virus or by mutated self proteins.

MHC class I genes are enormously polymorphic, and each class I molecule has its own preferred peptide-binding motif to accommodate a different range of peptides 8 to 10 amino acids long (the polymorphism guards against a pathogen evolving away from producing sequences that bind MHC) (*2*). To ensure a best fit of the T cell receptor repertoire with foreign antigens outside the thymus, T cells within the thymus that bear receptors with low-binding affinity for one's own peptides (in the context of an MHC complex) are selected to survive. MHC class I molecules on the surface of thymus cortical epithelial cells select the CD8$^+$ T cell repertoire, whereas MHC class II molecules select the CD4$^+$ T cell repertoire (*3*).

Variation in the makeup and proteolytic specificity of thymus proteasomes has been noted previously (*4*). Murata *et al.* discovered a



A degradation machine of its own. Proteasomes in the thymus contain a unique component that alters their proteolytic activity. This allows a range of peptides (bound to MHC molecules) to be expressed at the cell surface and function in T cell selection.

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