Frontier Physics with Correlated Electrons

Robert J. Birgeneau and Marc A. Kastner

In the mid-1970s, many solid-state physicists, including ourselves, felt that our field was reaching maturity. The independent electron approximation worked marvelously well for most semiconductors and metals; the phase transition problem was solved; and the fundamentals of magnetism, ferroelectricity, and superconductivity appeared to be well in hand. There were some niggling concerns; for example, we still did not know why nickel oxide was an insulator rather than a metal. However, many of us suspected that this was a detail that would be worked out in due course. As this issue of *Science* dramatically exemplifies, our self-satisfaction was completely misplaced. A remarkable variety of new (and in some cases, old) materials have been discovered that cannot be understood at all with traditional ideas. These have in common the dominant role played by electron-electron interaction effects, and hence such systems are collected together under the general rubric of "highly correlated electron systems." Examples are transition metal oxides, including, most spectacularly, the copper oxide high-temperature superconductors; heavy fermion metals, which typically involve rare earths or actinides; organic charge transfer compounds; and one- and two-dimensional electron gas systems. The possibilities for technological applications of some of these compounds are tantalizing, but they also present some of the deepest intellectual challenges in physics.

These materials are typically characterized by the coexistence of different kinds of order, including charge and orbital and spin density waves, together with superconducting and magnetic order. Indeed, these different kinds of ordering, which are conventionally thought to compete with each other, instead often appear to be synergistic in these materials. Such systems may also exhibit quantum fluid ground states and exotic transitions from ordered to quantum disordered states at absolute zero temperature. The mathematical apparatus required to describe the physics of highly correlated electronic systems is still under development. The most elegant results have been obtained by mapping the solid-state problem onto an equivalent field theoretical model developed by particle theorists and then using the mathematical apparatus of field theory to determine the ground state and the low-lying excitations. Deep insights have also been gained from numerical calculations taking advantage of modern powerful computers and new, very efficient algorithms. Clearly, highly correlated electron systems present us with profound new problems that almost certainly will represent deep and formidable challenges well into this new century.

"A remarkable variety of new...materials have been discovered..."

To date, this field has been largely driven by experimental discoveries. We particularly admire the research done in Japan. Interestingly, one of the reasons why Japanese scientists have played a leadership role in this field is that physicists who specialize in both synthesizing new materials and growing large single crystals have always held revered positions in Japanese universities. Historically, this has not been the case in U.S. universities. U.S. scientists also envy the very large investments that other societies, especially Western Europe and Japan, are making in this field. In the United States, support for university research in solid-state physics has simply not kept pace with the progress and interest in the fundamental scientific problems posed by correlated-electron materials. In addition, neutron scattering is an absolutely indispensible tool for studying the exotic magnetic and charge ordering exhibited by highly correlated electronic systems. Not surprisingly, therefore, the recent permanent closing of the High Flux Beam Reactor at Brookhaven National Laboratory has sent shock waves through the U.S. solid-state physics community. Given the importance of this field from both the fundamental and, prospectively, practical points of view, one might hope that these funding and facility handicaps would be addressed as soon as possible.

EDITORIAL

LETTERS

ESSAYS ON SCIENCE AND SOCIETY

POLICY FORUMS

BOOK AND NEW MEDIA REVIEWS

PERSPECTIVES

TECH.SIGHT

REVIEWS

Robert J. Birgeneau is the Cecil and Ida Green Professor of Physics and Marc A. Kastner is the Donner Professor of Science and head of the Department of Physics at the Massachusetts Institute of Technology.