Measuring Fermi Surfaces in Extreme Magnetic Fields

John Singleton

National High Magnetic Field Laboratory Pulsed-Field Facility, Los Alamos

Around 70 years ago, someone, very likely the eminent Russian physicist Ilya Lifshits, coined the term “a metal is a solid with a Fermi surface”. There is no better definition; the Fermi surface is the constant-energy surface which at zero temperature separates the occupied electron states from the empty ones in momentum space. If we know the size and shape of a metal’s Fermi surface, we understand how its free electrons behave and hence can account for almost all of its electrical, thermal and magnetic properties (and some mechanical ones as well). The definition has also expanded our idea of what constitutes a metal to include such diverse systems as electrically conducting organic compounds, certain oxides and reduced-dimensionality semiconductor devices.

In this lecture, I shall describe how high magnetic fields can be used to measure the size, shape and density of electronic states associated with the Fermi surfaces of the above systems. The topics covered include magnetic quantum oscillations (including the de Haas-van Alphen and Shubnikov-de Haas effects), the Hall effect, magnetoresistance and angle-dependent magnetoresistance oscillations. For those who are interested in applying these techniques to their samples, I shall include details of the necessary equipment.

John Singleton is a condensed-matter physicist who has spent over forty-five years applying high magnetic fields to a wide variety of materials. After an academic career at the Universities of Nijmegen and Oxford, he moved to the National High Magnetic Field Laboratory Pulsed-Field Facility in Los Alamos, New Mexico, where he leads the Magnet Operations, Science and Technology Team. He is the author of about 500 papers and a well-known textbook on the electronic properties of materials.

Crystal growth and material discovery - from tabletop to state-of-the-art

Eteri Svanidze

Max Planck Institute for Chemical Physics of Solids, Dresden, Germany
svanidze@cpfs.mpg.de

Over the past decades, quantum materials – materials in which quantum phenomena govern physical properties – have become essential to everyday applications. In most cases, technological advances are driven by the discovery of new solid-state materials and by a deeper understanding of existing ones. In this talk, I will present several families of solid-state materials discovered in our group. Our approach is guided not only by intuition, but also by a close dialogue between chemistry and physics, and between theory and experiment.

First, I will discuss some of the empirical tools for targeting new materials with desired properties (*1*, *2*). From a chemical perspective, we are looking at diverse compounds, ranging from crystallographically simple (*3*) to fairly complex – with as many as 444 atoms per unit cell (*1*, *4*). While the former can be supported by theoretical insights, the only way to establish the properties of the latter is to make and experimentally study them. By employing new methodology, we can access materials that so far remained out of reach due to their toxicity, radioactivity, or air sensitivity (*4*–*6*). Furthermore, we develop new ways to extract properties from micro-scale grains, extracted from multi-phase samples (*7*–*9*). In superconductors, we tune the critical temperature by making minute changes in the crystal structure (*10*, *11*). Among magnetic compounds, we examine not only strongly correlated systems that host exceptionally heavy electron masses at low temperatures (*11*), but also room temperature magnets that have application potential. Our experimental explorations go hand-in-hand with theory – we have targeted and confirmed a plethora of topological features (*12*). Furthermore, functional materials offer a promise of applications – from spintronics to peculiar thermoelastic behaviors (*13, 14*).

Eteri Svanidze Group leader at of the Research of Exotic Actinide- and Lanthanide-based Materials (REALM) group at MPI CPfS Dr. Svanidze's work focuses on the discovery and design of quantum materials, particularly compounds and alloys that exhibit unconventional superconductivity, magnetism, and other correlated electronic behaviors. Bachelor's degree in Physics and Mathematics from the State University of New York (Fredonia, USA) in 2009. Master of Science in Applied Physics from Rice University (Houston, USA) in 2011. PhD thesis, "Itinerant Magnets Composed of Nonmagnetic Elements," completed in 2015 under the supervision of Prof. Emilia Morosan. Postdoctoral fellow at the MPI CPfS from 2016 to 2017. Fulbright Research Chair at McMaster University (Hamilton, Canada) and the Centro Brasileiro de Pesquisas Físicas (Rio de Janeiro, Brazil) in 2018. https://www.cpfs.mpg.de/realm-group

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Calculating Fermi Surfaces (and Other Properties of Crystals) Using Density Functional Theory

Bartlomiej Wiendlocha

Faculty of Physics and Applied Computer Science, AGH University of Krakow, Al. Mickiewicza 30, 30-059 Krakow, Poland

Density functional theory (DFT), established in the 1960s by Pierre Hohenberg, Walter Kohn, Lu Jeu Sham, and others, laid the foundations for theoretical investigations of the electronic structure of crystalline materials. Owing to the development of computational methods and the rapid growth of available computing power, DFT has advanced significantly over the last decades, becoming an indispensable tool in solid-state physics and materials engineering. It enables the investigation, prediction, and interpretation of the electronic structure of materials and the properties that depend on it.

In this lecture, I will present the fundamentals of DFT and examples of its application to the study of electronic, dynamical (phonons), superconducting (electron-phonon interaction), magnetic, and thermoelectric properties of materials.

Bartlomiej Wiendlocha is a university professor at the Faculty of Physics and Applied Computer Science of AGH University of Krakow. For more than 20 years, he has used DFT methods to explain and predict material properties, focusing on functional materials such as thermoelectrics and superconductors.

Discovering New Superconductors: Successes, Failures, and Practical Insights

Tomasz Klimczuk

Faculty of Applied Physics and Mathematics and Advanced Materials Centre,
Gdansk University of Technology, Gdańsk, Poland.

Superconductivity and superconductors have been known for over a century, yet they remain a rather enigmatic class of materials whose practical applications are still very limited. This is mainly due to the need to cool them below a characteristic temperature known as the critical temperature. Thus, the search for new materials exhibiting superconductivity - and even better, new families of superconductors - remains an important topic in solid-state chemistry or material science.

In Gdańsk, we discovered more than a dozen new superconductors, although the term “new” sometimes refers to a known material that had not yet been tested at cryogenic temperatures. However, we had the most fun discovering new chemical compounds with a novel structural type that lacks central symmetry (!), and this compound turned out to be a superconductor at the relatively high temperature of 7 K.

In this lecture, I will describe our strategy for searching for new superconductors. In the second part, I will focus on three methods for measuring superconducting properties, which are necessary to confirm the presence of superconductivity and allow us to determine the most important parameters of the superconducting state.

Tomasz Klimczuk graduated from the Faculty of Applied Physics and Mathematics at the Gdansk University of Technology with a degree in physics. A breakthrough in his academic career came when he was awarded the Columbus Scholarship by the Foundation for Polish Science (FNP), which enabled him to join the research group of Prof. Robert Cava at Princeton University (2003–2005). In 2006, Dr. Klimczuk began a postdoctoral fellowship as a Director-Funded Postdoctoral Fellow at Los Alamos National Laboratory (LANL). Three years later, he moved to the Institute for Transuranium Elements at the Joint Research Centre of the European Commission in Karlsruhe. For the past fourteen years, he has been developing and leading a research group at Gdańsk University of Technology. His research focuses primarily on the synthesis and physical properties of novel materials.

All classes will be held in Room 3/07 of the Nanotechnology Center A.

SCHOOL SCHEDULE:

Friday, 19/06/2026:

- 9:15-10:45 John Singleton, Measuring Fermi Surfaces in Extreme Magnetic Fields
- 11:00-12:30 Bartłomiej Wiendlocha, Calculating Fermi Surfaces (and Other Properties of Crystals) Using Density Functional Theory

Note:

Prof. Singleton and Prof. Svanidze will also give seminars beginning at 13:15 in room NE 309. More details will be announced by Advanced Materials Centre.

Saturday, 20/06/2026:

- 10:15-11:45 Eteri Svanidze, Crystal growth and material discovery - from tabletop to state-of-the-art
- 12:00-13:30 Tomasz Klimczuk, Discovering New Superconductors: Successes, Failures, and Practical Insights