Dirac materials are the subject of great interest among researchers, with scientists seeking to make full use of their low-energy electronics properties. We spoke to **Professor Alexander Balatsky** about his work in investigating the properties of Dirac materials and searching for ways to modify their functionality, work which could widen their range of potential applications

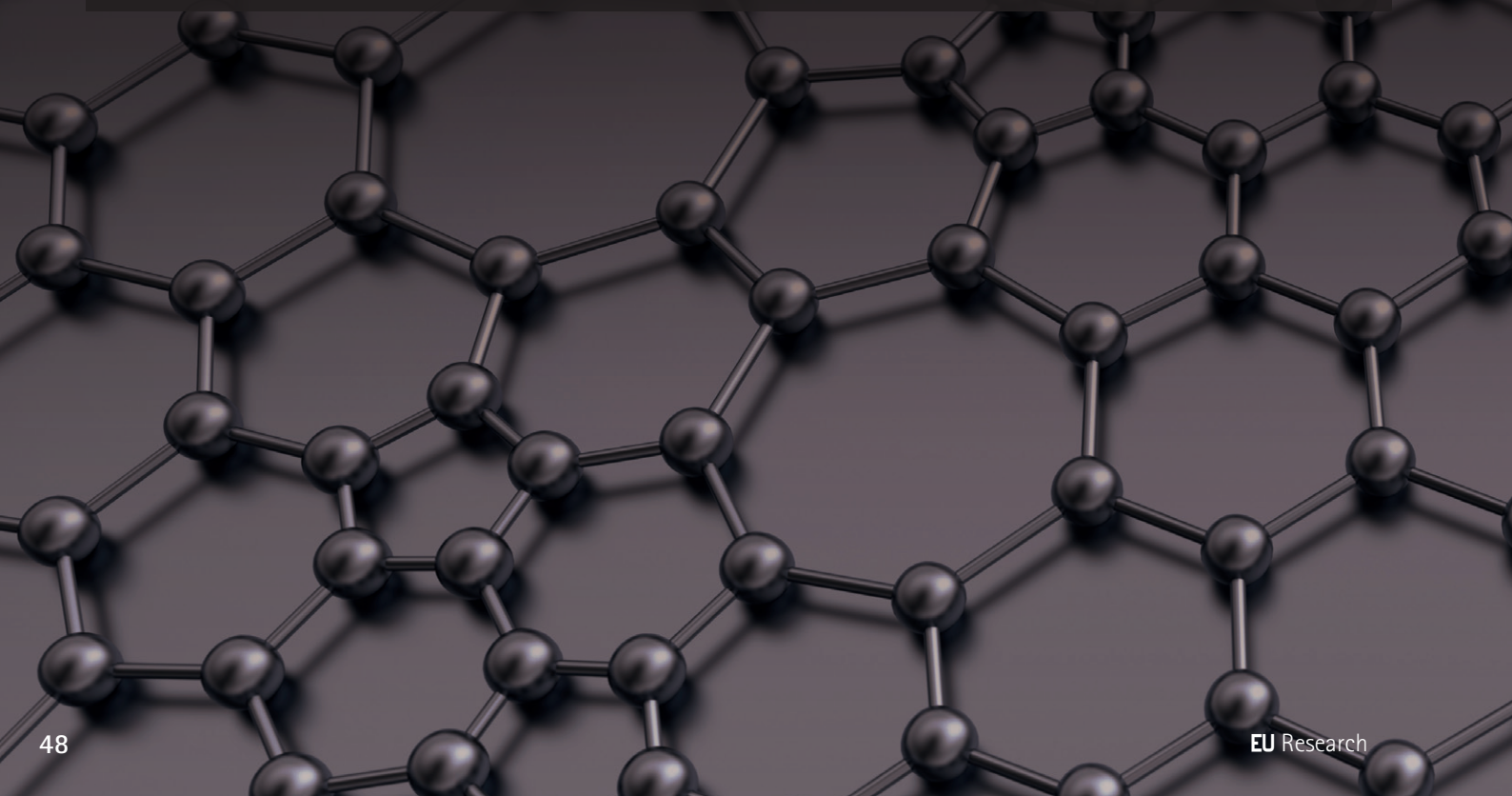
A peek into the future of material design

A sub-class of conducting materials characterised by the presence of nodes in the momentum space, the low energy electronic properties of Dirac materials hold important implications for the future of material design. Based at the Nordic Institute for Theoretical Physics in Stockholm, Professor Alexander Balatsky is the Principal Investigator of a research project which aims to harness the properties of these materials. "The idea behind the project is to take the functionalities of Dirac materials and investigate what intelligent suggestions we can make to take advantage of these properties," he outlines. Examples of Dirac materials include D-wave superconductors, graphene and topological insulators, which all share certain common features. "With Dirac materials, we see excitations of particles that are concentrated in small regions on the phase space. The crucial difference between Dirac materials and conventional metals is that typically fewer of these low-energy excitations are found in Dirac materials compared to conventional metals like copper," explains Professor Balatsky.

Material functionality

These features play a large role in determining the functionality of a material and its suitability for common applications. The project is looking at the functionality of Dirac materials in a fairly broad sense, where the properties of the material can be dramatically changed by relatively small modifications. "The presence of low-lying excitations enables the functionality of a material. The excitations of quasi-particles leave the material as a low-energy vapour around the Fermi surface," says Professor Balatsky. The Fermi surface can be thought of as a boundary within a material, which delineates occupied and unoccupied states; Professor Balatsky says Dirac materials have some distinguishing characteristics in this respect. "Instead of a Fermi surface, we see that there is a drastically reduced low energy phase space, or gap, available to produce low-energy excitations," he explains. "The active regions where we see electron and hole excitations are called Dirac nodes as they are showing up as lines and points."

Researchers are investigating the fundamental principles behind the emergence of these Dirac nodes, work



which could hold important implications in terms of material functionality. The Dirac equation, which describes the linear dispersion (energy/momentum) relation of electrons at relativistic speeds, is an important element of this work, providing a framework to predict the behaviour of particles within a material. "The Dirac equation describes the behaviour of fermions, and can also be used to describe the behaviour of bosons," outlines Professor Balatsky.

This is central to understanding the emergence of Dirac nodes. The presence of Dirac nodes in Dirac materials is typically controlled by forms of symmetry of the lattice; Professor Balatsky says the nature of the symmetry depends on the material. "If you look at topological insulators, the presence of the Dirac nodes is related to the spin-orbit coupling that connects the motion of electrons with the spin and the time-reversal symmetry of the material. In the case of graphene, it's an inversion symmetry," he explains. These symmetries are highly complex in the cases of some materials, yet once the symmetry is established, Professor Balatsky says it is possible to look towards describing the material as a Dirac material. "Once you have identified the nodes, you can make some universal statements about the behaviour of electrons, or excitations, in those nodes," he says.

This work in investigating the emergence of Dirac nodes is an essential step towards modifying the properties of these low-energy excitations in the nodes. This would offer exciting potential, enabling researchers to open energy gaps and control the electronic state of materials. "Once the nodes are present we can look at the ways of modifying their properties and hence changing the properties of the material - like make it insulating instead of being conductive. We would be able to drastically change the response of materials at low energies. And we would be able to achieve this by modifying only a very few points on the surface," explains Professor Balatsky. The gap in Dirac materials can be tuned, enabling researchers to modify their functionality. "For instance, we can make a material that reflects specific frequencies of light," he outlines.

The idea behind the project is **to predict properties of Dirac materials** and investigate what intelligent suggestions we can make to take advantage of these properties

Artificial Dirac Materials

The development of new technologies over the last twenty years has greatly improved researchers' ability to manipulate metals at atomic scales, opening up new possibilities in terms of tuning and modifying material functionality. Researchers are now finding that it is possible to build artificial materials where Dirac nodes can be introduced on-demand, at specific points within the overall structure. "We can essentially place the atoms, quantum dots, or certain particles, in certain positions in the lattice. That's very exciting," says Professor Balatsky. Researchers plan to use the sensitivity of nodes in the electron spectrum of Dirac materials to induce controlled modifications of the Dirac nodes. "We're very interested in exploring the behaviour of these Dirac materials when we see certain responses," says Professor Balatsky.

This work could both significantly enhance researchers' theoretical understanding of Dirac materials, and also have a significant practical impact on material design. With a deeper theoretical knowledge of Dirac materials, materials could be designed to tune the energy profiles of Dirac carriers, helping to improve energy efficiency. "This research will contribute to an improved understanding of thermo-electrics, essentially looking at how we can control heating elements and make them more efficient. We are investigating how we can control conductivity," continues Professor Balatsky.

This research is central to the potential future applications of Dirac materials.

At a glance

Full Project Title
DM Dirac Materials

Project Objectives
The discoveries of superfluid phases in Helium 3, high T_c superconductors, graphene and topological insulators have brought into focus a class of materials where quasiparticles are described by the Dirac equation, the same equation governing the behavior of relativistic particles. Materials in this class, Dirac materials[1], exhibit unusual universal features such as: Klein tunneling, chiral symmetries, and impurity resonances. The objective of this project is to explore the properties shared by these materials and discuss the unique role of symmetries that protect the Dirac spectrum. Our results will expand our theoretical understanding and guide the design of materials and engineered geometries that allow tunable energy profiles of Dirac carriers and realization of states, like Dirac bosons[2], which cannot be found in nature.

Project Partners
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[1] T.O. Wehling, A.M. Black-Schaffer & A.V. Balatsky (2014) Dirac materials, Advances in Physics, 63:1, 1-76

[2] S. Banerjee, J. Fransson, A. M. Black-Schaffer, Hans Ågren, and A. V. Balatsky, Granular superconductor in a honeycomb lattice as a realization of bosonic Dirac material [1] Phys. Rev. B 93, 134502 (2016)

Professor Alexander V. Balatsky

Alexander V. Balatsky obtained his doctoral degree from the Landau Institute for Theoretical Physics. After postdoctoral training and a research assistant professor position at the University of Illinois at Urbana Champaign, he went to Los Alamos National Laboratory as an Oppenheimer Fellow where, in 2014, he became director of the new Institute for Functional Materials. Over the past several years he has been elected as a Fellow of various prestigious organizations: Fellow of the American Physical Society in 2003, Los Alamos Fellow in 2005, and the American Association for the Advancement of Science Fellow in 2011.

While a number of applications of graphene have been identified for example, in fields as diverse as energy, biomedicine, and composites and coatings, the applicability of a material depends heavily on its functionality, reinforcing the wider importance of Professor Balatsky's research. "We're continuing to look at interesting expressions of these Dirac equation structures and Dirac nodes," he says. Many of the general features of Dirac materials have also been observed in other areas of materials science. "Dirac materials are a sub-class of metals – graphene is a prominent example, but there are also others. There are also unconventional super-conductors, such as high temperature super conductors. As research has progressed, we've seen the same descriptions, the same phenomena, emerging from different parts of materials science research," says Professor Balatsky.

Research will continue into both the potential applications of Dirac materials, and fundamental questions around their applications for energy efficient electronics applications. "We're investigating the non-equilibrium state of Dirac excitations. We describe transient and time dependent novel states that one can generate in the Dirac nodes by applying pulses of light, magnetic and electric fields to Dirac materials. A natural analogy would be - if you stretch a spring out of equilibrium for a while it can take certain shapes. But these very interesting states are not available in equilibrium. We are looking for the novel states of Dirac materials that are not available in the equilibrium," says Professor Balatsky. There is also significant scope for further research into the functionalisation of Dirac materials. With the development of new imaging and manipulation techniques there is significant potential to capture exciting new phenomena in quantum materials, opening up new avenues of research and potential applications.

Condensed Matter group at Nordita: Front row: (left to right) S. Pershoguba, S. Borysov, C. Triola; Second row: (left to right) A.Balatsky, Y. Kedem, M. Geilhufe, A. Pertsova.