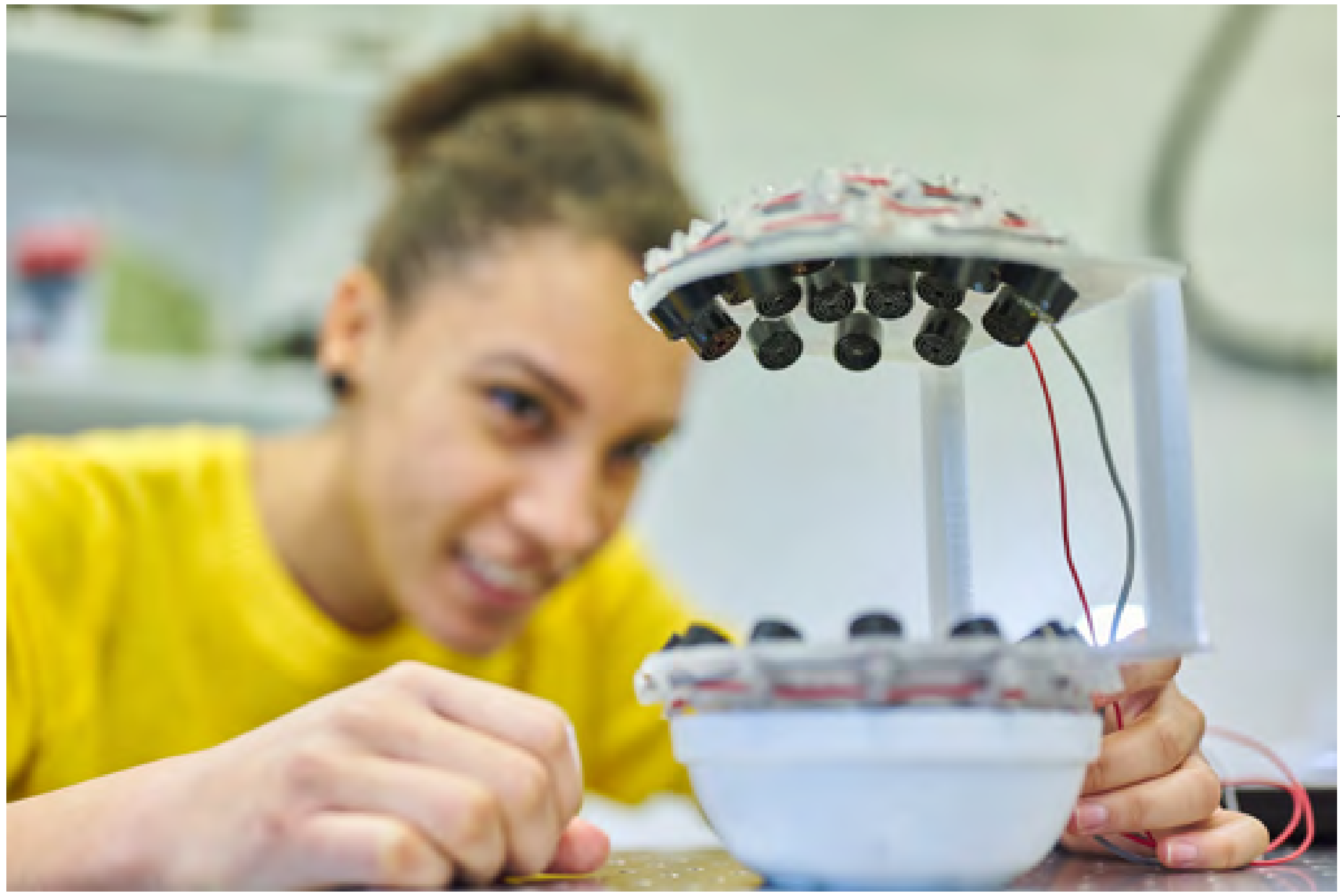

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Contactless examination of suspended particles in an acoustic trap

Faculty of Physics

While 2019 was largely unaffected by the coronavirus, the pandemic soon became the defining aspect of 2020. The research that has been conducted under pandemic conditions is vastly different from that carried out in the past.
Nonetheless, this research report clearly demonstrates that the scientists of the Faculty of Physics were able to work on a wide range of very interesting topics in the past year. Professor Heiko Wende and his team are exploring ways of solving the problem of heat generation in microelectronics, for instance. Professor Axel Lorke's research group seeks to trace the movement of a single electron within an electronic component. Professor Marika Schleberger's group grapples with the question of whether it is feasible to develop a graphene-based pressure sensor that can detect gases with the highest possible precision. The team around Professor Michael Schreckenberg studies communication between automated and non-automated road users and the question of whether it can improve the efficiency and safety of road traffic.
Major milestones of the past two years included the Faculty's participation in the newly established DFG Collaborative Research Centre/Transregio CRC/TRR 270 'Hysteresis Design of Magnetic Materials for Efficient Energy Conversion' in 2019 and the extension of CRC 1242 'Non-Equilibrium Dynamics of Condensed Matter in the Time Domain'.

Pretty tiny – from individual electrons to nanoparticles

From individual electrons to new electrochemical applications

Professor Axel Lorke and Dr Paul Geller were able to trace the movement of individual electrons through an electronic component within the scope of several DFG-funded projects. Minuscule semiconductor nanoparticles called 'quantum dots' display characteristic optical properties depending on their charge state. A single electron determines whether a quantum dot emits light when exposed to laser irradiation. If its charge state changes, the dot produces a characteristic flashing pattern, which shows whether it has just captured or emitted an electron. Professor Jürgen König's research group has evaluated these 'optical telegraph signals' together with the CRC 1242 team.

Metal nanoparticles made from platinum are used to convert chemical into electrical energy, for example, in fuel cells or when generating hydrogen as a power source. For the EU-funded project 'MoreInnoMat', Dr Nicolas Wöhrl of Professor Axel Lorke's research group successfully worked with Professor Stephan Schulz's (Chemistry) group on developing a process for synthesising carbon nanowalls with embedded platinum nanoparticles. In the process, for which a patent application has been filed, two-dimensional carbon atom layers (graphene) are closely connected to platinum nanoparticles, which makes the structure particularly sturdy for practical application.

Nanoscale magnetic systems

Professor Michael Farle's research group studies the properties of nanoscale magnetic systems. Synthesis of new materials has enabled a variety of new applications, such as the use of efficient permanent magnets in electric motors and magnetocaloric materials in innovative cooling technologies. The researchers are studying these and other applications intensively within the scope of the new DFG Transregio CRC/TRR 270, working together with colleagues from TU Darmstadt. Besides nanoparticles for additive manufacturing (3D printing), they are producing special magnetic Heusler compounds, in which small ferromagnetic particles (< 2 nm) in an antiferromagnetic matrix exhibit very high coercivity at room temperature.

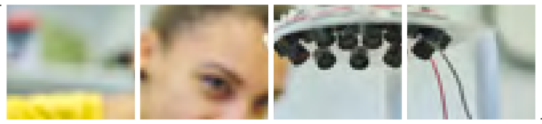
Researchers in the DFG project 'Magnetic Landscapes' use laterally periodically modulated magnetisation to examine ultra-thin layers and control spin wave phenomena in the sub-terahertz range. Another key research area is the development of hybrid nanoparticles for medical theranostics. This is the focus of the EU-funded 'MaNaCa' project, a collaborative endeavour involving colleagues from Greece and Armenia. Its combination of therapy and diagnostics in magnetic nanoparticles paves the way for new approaches to treating cancer.

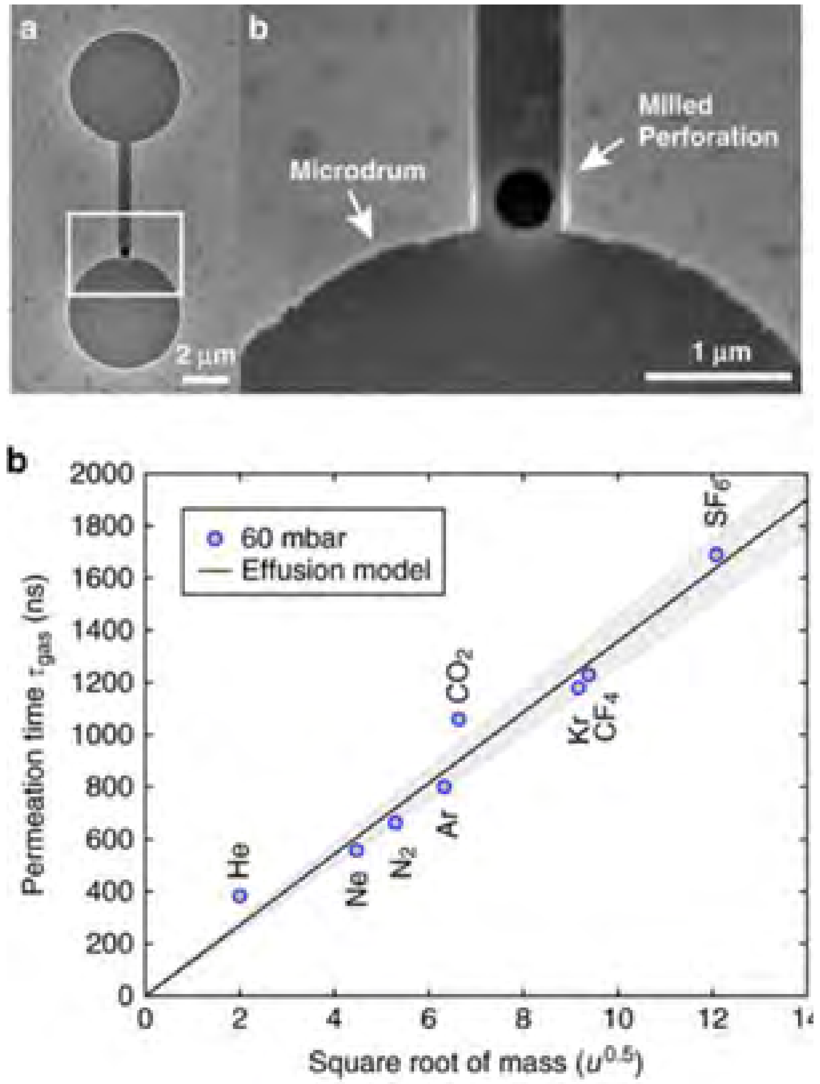
The effect of the hot electron

You may not really see them, but you can still trace the energy flow with your naked eye. It's a bit like thumbing through a flip book: a team of scientists from the groups of Professor Uwe Bovensiepen, Professor Rossitza Pentcheva and Professor Heiko Wende has investigated energy transfer in a metal insulator material. In the long term, their findings may contribute to a solution for the problem of heat generation in microelectronics through precise material design. Any attempt to get to the bottom of this phenomenon will inevitably lead to the atomic level and, as such, to electrons making their way through various materials. But how exactly do they do this?

That is what UDE physicists are studying in CRC 1242 'Non-Equilibrium Dynamics of Condensed Matter in the Time Domain'. They have analysed the layer structures of the metal insulator material using a pump-probe process. A laser pulse feeds energy into the system. This energy stimulates the electrons and 'heats them up', so to speak. Soon after, an X-ray determines from a snapshot how the 'hot' electrons spread through the material.

The result: the hot electrons stimulate the metal lattice within less than a picosecond. Almost simultaneously, the interface between the materials begins to oscillate. Surprisingly, the insulator reacts just a picosecond later. Theoretical simulations have confirmed the significance of interface oscillations.





Electron microscope image of a graphene pressure sensor. The permeation time through the membrane shows a linear increase with the square root of the particle mass.

Nanoparticles in the quantum regime

Quantum physics describes the microcosm perfectly. If we apply it to large objects rather than to atoms or photons, however, it tend to produce predictions that turn our traditional views of the world upside down. According to these predictions, a single object should be able to exist simultaneously in multiple places and even change its behaviour depending on whether or not it is observed. Professor Klaus Hornberger's research group studies systems that straddle the boundary between this quantum regime and traditional physics.

One of its research highlights in the past two years was the quantum-mechanical description of nanoparticles that are suspended by laser light and, as such, largely uninfluenced by environmental factors. The researchers have recently developed a feasible method of putting such a nanoparticle into the quantum-mechanical basic state of its centre-of-mass motion and rotational motion, i.e., cooling it to absolute zero. This method may be a point of departure for future fundamental experiments and technological applications on which the research group is working.

Electron tunnelling in quantum dots

The flow of electrical currents through conventional circuits involves a vast number of electrons. When circuits are realised in nanostructures, i.e., made very small, however, the current can be transported by much fewer electrons. During the transport of current through a quantum dot, individual electrons exhibit the tunnel effect: they successively jump back and forth between the electricity supply and the quantum dot. Such quantum jumps constitute the smallest possible unit of current transport. Their measurement provides the greatest possible amount of information that can be extracted from the system.

Professor Jürgen König's group develops theoretical tools that makes it possible to analyse electron tunnelling in quantum dots statistically in order to obtain important information about the underlying system. A highlight of this project has been the application of their theory to experiments carried out in Professor Axel Lorke's research group, in which electron tunnelling in quantum dots was measured with high precision using time-resolved methods. This allowed the researchers to determine the spin-relaxation time of an electron in a quantum dot among other insights.

Pretty flat – from thin layers to 2D materials

Two-dimensional magnetic semiconductors

Within the scope of its ongoing theoretical research into novel two-dimensional materials, Professor Peter Kratzer's research group has recently begun to examine materials with magnetic properties. Chromium(III) iodide CrI3 is a well-known member of this class of materials. A stack of atomically thin single layers that are magnetised in the same or different directions could function as an extremely compact, magnetic store of information in future. Due to variable electrical resistance, a current flowing perpendicular to the layers can be used to read stored information. Using a special calculation process, members of Professor Peter Kratzer's research group have successfully modelled the magnetic interaction between the layers and the ratio of resistance with identical and divergent magnetisation of the atomic layers in line with the experimental data. Their results may provide a basis for identifying alternative candidates for envisioned applications, i.e., materials with an altered chemical composition and, as such, enhanced magnetic functionality.

Nanoscale materials for energy conversion

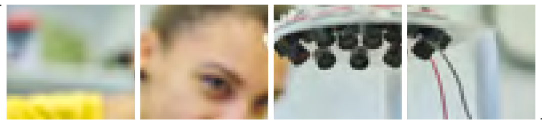
Professor Rossitza Pentcheva's research group uses high-performance computing systems for nonparametric quantum-mechanic modelling of novel materials used in electronic components and energy conversion.

Within the scope of CRC/TRR 80, researchers are studying the occurrence of new electronic phases at transition metal oxide interfaces. This includes topologically non-trivial states in oxide superlattices with honeycomb patterns and ultra-thin films whose properties change drastically under extreme tension, e.g., from a ferromagnetic metal to an antiferromagnetic insulator. Further research focuses on improving thermoelectrical properties by taking advantage of reduced dimension, e.g., in oxide heterostructures. This has led to a European patent. In CRC/TRR 247, researchers optimise anode materials for water splitting by precisely modifying their structural motifs, chemical composition and defects. CRC 1242 focuses on modelling the propagation of laser pulses through metal-insulator interfaces on an ultra-short time scale and the accurate description of spectroscopic properties through many-body theory. Last but not least, the newly established CRC/TRR 270 investigates how a combination of magnetism and lattices can increase the efficiency of magnetocaloric materials.

Dean: Professor Dr Michael Schreckenberg

Thin materials: graphene

Ultra-thin materials are en vogue. Right after their discovery, these materials with a thickness of only few atomic layers mostly attracted the attention of basic research. Recently, however, application-oriented research has become increasingly interested in them, too. The European Union recognised this potential at an early stage and established the Graphene Flagship in 2013. Within the flagship, a team of researchers from the Delft University of Technology (Professor Peter Steeneken's research group), the Université Basse Normandie and the University of Duisburg-Essen (Professor Marika



Professors

Professor Dr Uwe Bovensiepen
Professor Dr Richard Kramer Campen
Professor Dr Michael Farle
Professor Dr Thomas Guhr
Professor Dr Manuel Gruber
Professor Dr Hendrik Härtig
Professor Dr Klaus Hornberger
Professor Dr Michael Horn-von Hoegen
Professor Dr Boris Kerner
Professor Dr Jürgen König
Professor Dr Peter Kratzer
Professor Dr Axel Lorke
Professor Dr Samir Lounis
Professor Dr Frank Meyer zu Heringdorf
Professor Dr Martin Mittendorff
Professor Dr Rolf Möller
Professor Dr Hermann Nienhaus
Professor Dr Rossitza Pentcheva
Professor Dr Marika Schleberger
Professor Dr Martina Schmid
Professor Dr Claus M. Schneider
Professor Dr Michael Schreckenberg
Professor Dr Klaus Sokolowski-Tinten
Professor Dr Björn Sothmann
Professor Dr Heike Theyßen
Professor Dr Heiko Wende
Professor Dr Dietrich Wolf
Professor Dr Andreas Wucher
Professor Dr Gerhard Wurm

Schleberger's research group) has successfully built a graphene-based pressure sensor that can detect gases with extremely high precision. In this process, a small gas reservoir is sealed with a graphene layer that is less than a nanometre thick and perforated with defined pores. What is special about this sensor is that it does not rely on chemical reactions. Instead, detection is based on the permeation time of gases through the porous graphene membrane, which simultaneously functions as a gas pump and a pressure sensor. The idea behind it is simple: light gases are faster, so they escape the reservoir sealed by the membrane more quickly than heavy gases do. This system has a range of advantages over conventional sensors: the sensor is extremely small, fast and energy-efficient yet highly sensitive.

Next-generation solar cells

Material efficiency and more effective light conversion are key topics in photovoltaics. Professor Martina Schmid's research group develops next-generation thin-film solar cells. They are ultra-small or ultra-thin but still harvest sunlight efficiently when combined with optical concepts. In particular, the researchers have made important progress in their work on ultra-thin solar cells with an absorber made of Cu(In,Ga)Se2 applied to a transparent substrate. They have achieved an efficiency of nearly 13% for an absorber layer thickness of less than 500 nm, which trumps results achieved by other groups in the past. Additional improvements are expected as a result of combining the existing system with nano- and micro-optical concepts for targeted light harvesting. Ultra-thin solar cells with transparent back contacts can be used for a wide range of purposes in high-efficiency concepts and in the aesthetic aspect of building integration.

The world's thinnest films

Besides ultra-fast structural dynamics at solid-state surfaces, Professor Michael Horn-von Hoegen's research group studies the growth of the world's thinnest films. The researchers produce 2D materials, layers that are a single atom thick and exhibit completely novel properties compared to volume. They were able to decipher a new growth mode for monolayer boron or 'borophene', which is just as relevant to other materials: boron atoms are dissolved in a metallic substrate at a high temperature following the decomposition of a boronic precursor. They segregate to the surface while cooling and form a perfect monolayer of borone. The boron functions as a surfactant ('surface active agent') and smoothes the metallic substrate to grow as a perfect layer.

Pretty mobile

Physics of Transport and Traffic

Professor Michael Schreckenberg's research group 'Physics of Transport and Traffic' studies a wide range of topics related to mobility.

Within the scope of CRC 876 'Providing Information by Resource-Constrained Data Analysis', it collaborates with electrical engineers and computer scientists to analyse inner-city traffic. Its goal is to reduce traffic jams and travel times without expanding road capacity. The researchers examine various route selection optimisation methods and dynamic methods. They aim to expand the simulation model to account for the behaviour of (communicating) self-driving vehicles in order to simulate, analyse and optimise hybrid traffic.

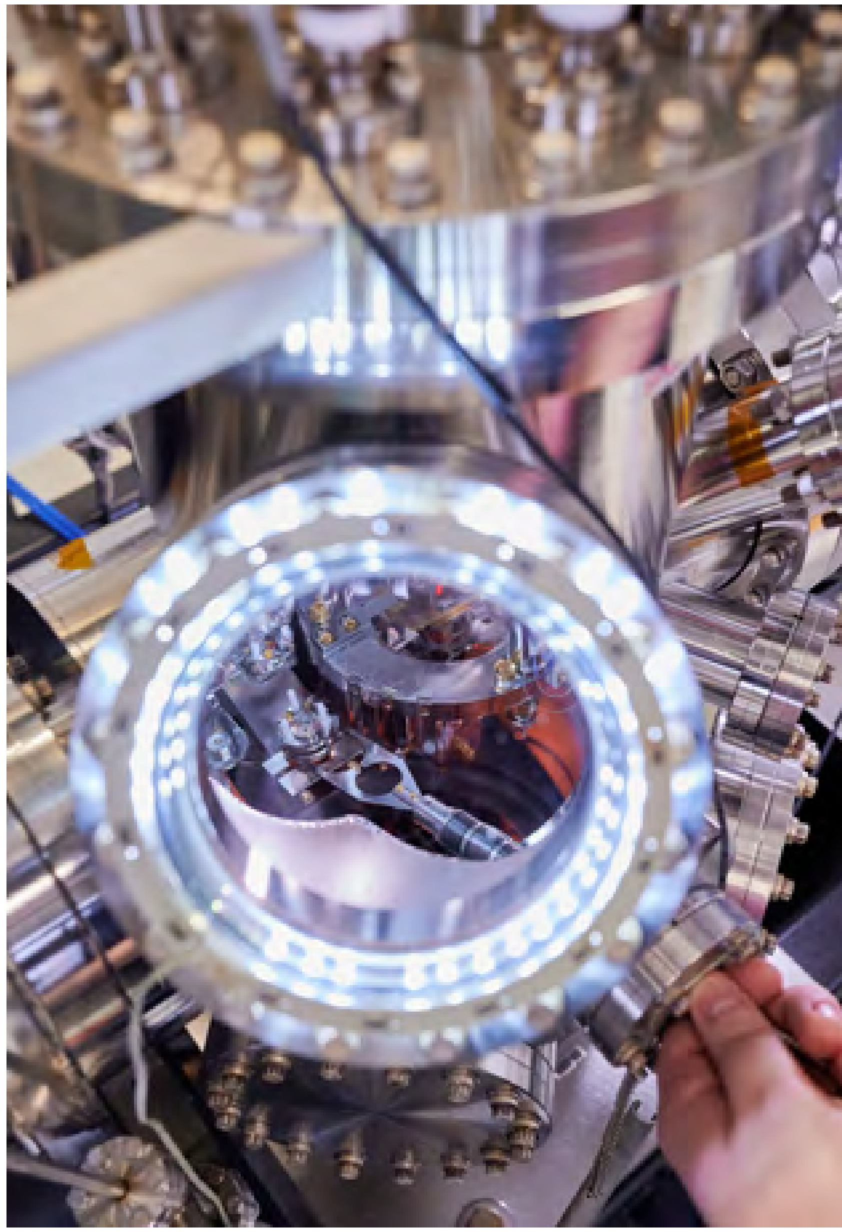
The LUKAS project, funded by the Federal Ministry of Economics and Technology, works on developing a local environmental model for cooperative automated driving. This collaborative research project aims to boost traffic efficiency and safety in the mixed traffic of urban spaces. Reliable cooperation through a fast, safe communication channel connecting automated and non-automated road users plays an important part in this endeavour.

Pretty big

Planet formation

Professor Gerhard Wurm's group focuses on planets and their formation. In a collaborative project, Professor Wurm's and Professor Dietrich Wolf's research groups at the UDE's Faculty of Physics and Professor Troy Shinbrot of Rutgers University were able to close a gap in our understanding of the formation of planetesimals. Their work has shown that particles in protoplanetary disks become electrically charged through impacts. As a result, millimetre-sized particles eventually become more stable, decimetre-sized aggregates. The process also connects various growth phases. Students of the Faculty entered and won an international competition with an idea based on these insights: they successfully investigated the discharge of particles through cosmic radiation on a high-altitude balloon.

The stability of planetesimals was also the focus of several parabolic flight campaigns. Using a low-pressure wind tunnel, researchers were able to quantify erosion boundaries at extremely low environmental pressure levels (few Pa) similar to those present in protoplanetary disks. The planet Mars was one of the group's research subjects, too. In the lab, they evaluated various known and novel processes that could potentially explain how ground particles can reach the thin atmosphere of Mars, which can be engulfed in a global cloud of dust over periods of months.



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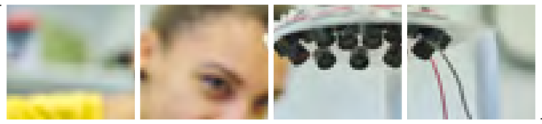
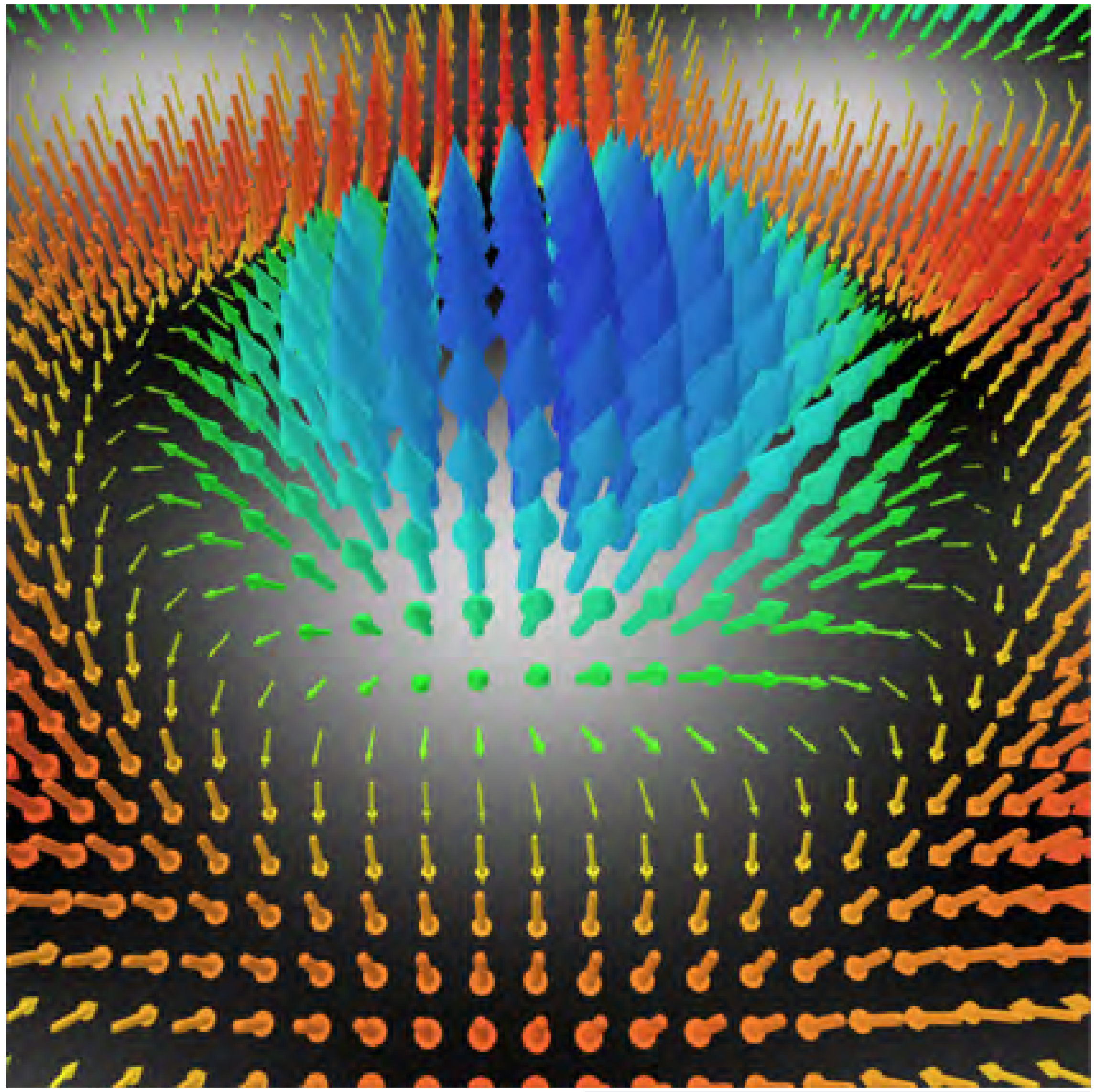
View into the vacuum chamber of an atomic force microscope during a sample change

Now I've got it – physics education

The research groups in the field of physics education conduct basic and developmental





© Foto: Davis et al., SCIENCE 368, eaba6415 (2020)

Reconstruction of the vector field of a plasmonic skyrmion created from experimental data

research into the acquisition of physics proficiency. Professor Heike Theyßen's and Professor Hendrik Härtig's research groups both conduct research in the field of experimental competencies, which involves projects on the individual advancement of experimental skills in general studies and ability-oriented experimental opportunities for pupils at lower secondary level.

The researchers in Professor Härtig's group further study the influence of language on learning physics. In this area, they plan and evaluate concrete learning opportunities and examine text comprehension difficulties in physics. Professor Heike Theyßen's group focuses on the development of diagnostic skills in teacher training students.

Pretty quick

Professor Frank Meyer zu Heringdorf's group researches the emission of electrons from electron density waves, so-called surface plasmon polaritons within the DFG Collaborative Research Centre CRC 1242. By advancing the photoemission microscopy method, the researchers succeeded in reconstructing the electric fields of such plasmon waves with a nanometre resolution and a time resolution of one millionth of a billionth of a second in three dimensions. The researchers used a first (pump) laser pulse to generated a plasmon wave on a nanostructured gold surface, which then moved across the surface at nearly the speed of light. A second (probe) laser pulse was used to image the plasmon wave in the microscope by means of nonlinear photoemission.

Ultra-fast phenomena in solid-state bodies and at surfaces

Professor Uwe Bovensiepen's and Professor Klaus Sokolowski-Tinten's research group focuses on the microscopic interaction mechanisms in play between electronic, magnetic and structural degrees of freedom in condensed matter. The group aims to gain an understanding of the energy exchange taking place between the individual sub-systems and the energy transport in nanoscale materials. Its members use measurement techniques with a high temporal and spatial resolution and a specific sensitivity for the individual degrees of freedom. The group's research spans a wide range of questions: electron dynamics at icy surfaces, spin transport in thin magnetic layers, the non-equilibrium dynamics of photonic stimulation in heterostructures, and rapid changes of the lattice structure of phase-change materials, which constitute the basis of modern electronic storage systems.

CRC 1242: 'Non-Equilibrium Dynamics of Condensed Matter in the Time Domain'

Researchers in the Collaborative Research Centre 1242 'Non-Equilibrium Dynamics of Condensed Matter in the Time Domain' seek to gain a microscopic understanding of dynamic processes in condensed matter.

Selected Publications

Davis, T.J., D. Janoschka, P. Dreher, B. Frank, F.-J. Meyer zu Heringdorf, H. Giessen (2020)*: Ultrafast vector imaging of plasmonic skyrmion dynamics with deep subwavelength resolution, Science 368, 6489.*

Geisler, B., R. Pentcheva (2020): *Fundamental difference in the electronic reconstruction of infinite-layer vs. perovskite neodymium nickelate films on SrTi03(001), Phys. Rev. B 102, 020502(R), (Rapid Communications, Editor's suggestion).*

Härtig, H., N. Fraser, S. Bernholt, J. Retelsdorf (2019): *Kann man Sachtexte vereinfachen? Ergebnisse einer Generalisierungsstudie zum Textverständnis. In: Zeitschrift für Didaktik der Naturwissenschaften 25, 1–15.*

Kurzmann, A., P. Stegmann, J. Kerski, R. Schott, A. Ludwig, A. D. Wieck, J. Koenig, A. Lorke, M. Geller (2019): *Optical Detection of Single-Electron Tunneling into a Semiconductor Quantum Dot. Phys. Rev. Lett. 122, 247403.*

Neumann, K., H. Schecker, H. Theyßen (2019): *Assessing Complex Patterns of Student Resources and Behavior in the Large Scale. The Annals of the American Academy of Political and Social Science 683 (1), 233–249.*

Rosłoń, I. E., R. J. Dolleman, H. Licona, M. Lee, M. Šiškins, H. Lebius, L. Madauß, M. Schleberger, F. Alijani, H. S. J. van der Zant, P. G. Steeneken (2020): *High-frequency gas effusion through nanopores in suspended graphene, Nature Communications 11, 6025.*

Sarkar, S., P. Kratzer (2020): *Electronic correlation, magnetic structure, and magnetotransport in few-layer CrI3. Phys. Rev. Mater. 4, 104006.*

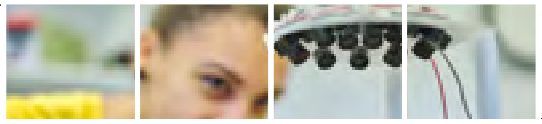
Steinpilz, T., K. Joeris, F. Jungmann, L. Brendel, J. Teiser, D. Wolf, T. Shinbrot, G. Wurm (2020): *Electrical Charging Overcomes the Bouncing Barriers in Planet FormaRon, Nature Physics 16, 225–229.*

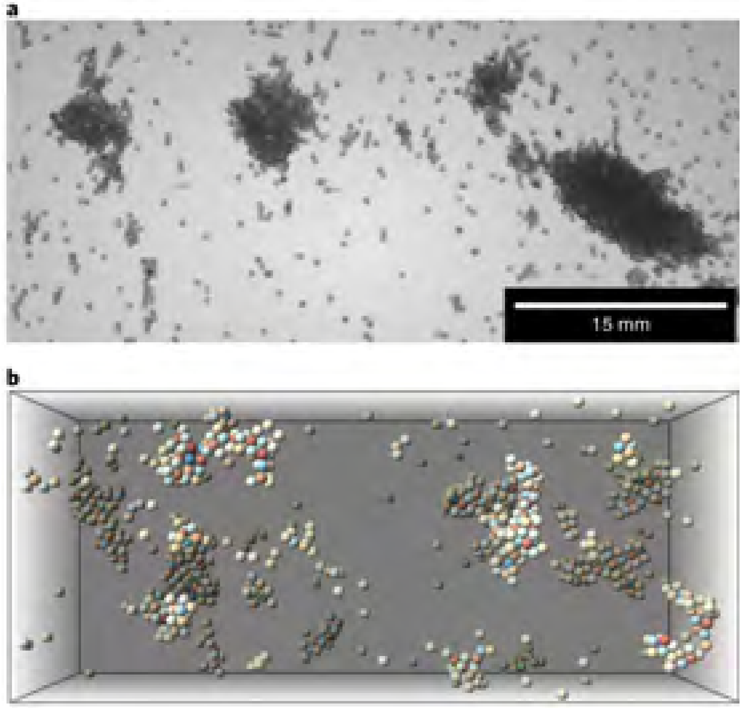
Terwey, A., M. E. Gruner, W. Keune, J. Landers, S. Salamon, B. Eggert, K. Ollefs, V. Brabänder, I. Radulov, K. Skokov, T. Faske, M. Y. Hu, J. Zhao, E. E. Alp, C. Giacobbe, O. Gutfleisch, H. Wende (2020): *Influence of hydrogenation on the vibrational density of states of magnetocaloric LaFe11.4Si1.6H1.6. Phys. Rev. B 101, 064415.*

Vranken, T.P.E., M. Schreckenberg (2020): Cellular *Automata Intersection Model. Collective Dynamics, [S.l.] 5, 1–25.*

Yin, G., M. Song, M. Schmid (2019): *Rear point contact structures for performance enhancement of semi-transparent ultrathin Cu(In,Ga)Se2 solar cells. Solar Energy Materials and Solar Cells 195, 318.*

Zingsem, B.W., T. Feggeler, A. Terwey, S. Ghaisari, D. Spoddig, D. Faivre, R. Meckenstock, M. Farle, M. Winklhofer (2019): *Biologically encoded magnonics. Nature Communications 10, 4345.*





An experiment simulating the emergence of larger, electrically charged clusters as they develop from dust particles into planets

Their studies focus on dynamics far beyond the thermodynamic equilibrium created by very brief, external stimuli. Carried out exclusively in the temporal domain, their work closely combines experimental and theoretical methods.

During the first funding period (2016–2020), the researchers developed suitable research methods and analysed and described the dynamics within individual degrees of freedom, such as oscillation of the atomic core and electrical charge.

The ongoing second funding period (2020–2024) builds on the results achieved in the years before. It focuses on manipulating the dynamics processes in non-equilibrium. This approach serves two purposes: to expand current understanding of the phenomena involved and to trial adjustments of the time periods available for potential ultra-fast applications.

CRC/TRR 270: Hysteresis Design of Magnetic Materials for Efficient Energy Conversion

New magnets for future energy technologies

From strong, permanent magnets for wind turbines to electrical engines and materials for magnetic cooling: new functional materials are an indispensable component of a successful energy transition and a low-emission future. On 1 January 2020, TU Darmstadt and the University of Duisburg-Essen jointly launched the new Collaborative Research Centre CRC 270 'HoMMage'. It will be funded by the German Research Foundation (DFG) with around 12 million euros for an initial period of four years.

Awards

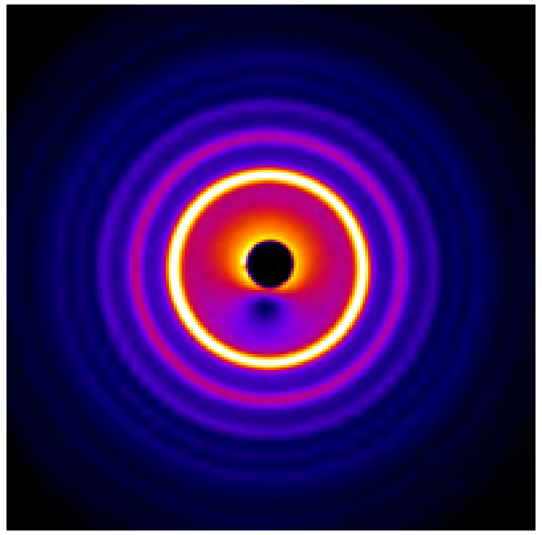
During the reporting period, several members of the Faculty of Physics won awards.

Dr Christian Schneider received a prize of 2,000 euros for his outstanding dissertation. Markus Heckschen received a prize of 1,000 euros for excellent academic performance. The CEO of Sparkasse Duisburg, Dr Joachim Bonn, and the Vice Chancellor of the University of Duisburg-Essen, presented both prizes to their recipients during a small ceremony.

Dr Nora Dörmann won the University of Duisburg-Essen's 2019 Diversity Prize in the managerial category. She is the Managing Coordinator of CRC 1242. The prize honours her commitment to supporting the group's researchers.

Dr Anna Grünebohm has secured one of the sought-after early-career research groups in the Emmy Noether Programme for her research into harmless and easily available materials for generating electricity from temperature differences or mechanical energy. The groups are endowed with 1.3 million euros in funding for a period of six years.

Professor Michael Farle has received a 'Mega Grant' (2019–2021) from the Ministry of Science and Higher Education of the Russian Federation. He researches magnetic MAX phases with Russian colleagues at the L.V. Kirensky Institute of Physics in Krasnoyarsk.



Electron refraction pattern of an Fe/MgO heterostructure, false-colour image

Dr Mehmet Acet received the Turkic Council's renowned science award for academic and technological research in 2018 (in the 2019 ceremony) for his groundbreaking work on the inverse magnetocaloric effect.

Dr Ulf Wiedwald was honoured by the German Federal Foreign Office and the Ministry of Foreign Affairs of the Russian Federation in 2020 for his outstanding contributions to the two countries' collaboration in science and education.

Outlook

With the appointment of four new professors, the Faculty's team has become younger. The extension of CRC 1242, the establishment of the new CRC/TRR 270 and many successful individual funding applications have given the Faculty access to significant third-party resources in addition to the funding provided by the University. These granted funds verify the excellent scientific output of the Faculty and provide highly favourable conditions for resuming regular scientific work after the lockdowns – for discussing, calculating, measuring, discarding, discussing again, writing and publishing together with several hundred highly motivated students.

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