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Press release
15 January, 2026

In the Basic Sciences category

The Frontiers of Knowledge Award goes to Allan MacDonald and Pablo Jarillo-Herrero for their discovery of the "magic angle" enabling science to transform and control the behavior of new materials

- **The "pioneering" work of the two physicists** has achieved both the theoretical foundation and experimental validation of a new field where superconductivity, magnetism and other properties can be obtained by rotating new two-dimensional materials like graphene
- **In a theoretical model published in 2001, Canadian Allan MacDonald predicted** that on twisting two graphene layers at a given angle, of around one degree, the interaction of electrons would produce new emerging properties
- **In 2018, Spanish scientist Pablo Jarillo-Herrero delivered the experimental confirmation** of this "magic angle" by rotating two graphene sheets in a way that transformed the material's behavior, giving rise to new properties like superconductivity
- **Their insights have opened the door to transformative applications** like the transmission of electricity with no energy loss, far more efficiently and sustainably, or the development of new electronic devices and quantum computing technologies

The BBVA Foundation Frontiers of Knowledge Award in Basic Sciences has gone in this eighteenth edition to physicists Allan MacDonald (The University of Texas at Austin) and Pablo Jarillo-Herrero (Massachusetts Institute of Technology, MIT) for their discoveries concerning the "magic angle" that allows the behavior of new materials to be transformed and controlled. What the committee terms the "pioneering" insights of the two researchers have provided both the theoretical foundation and experimental validation of a whole new field, now known as twistronics, where superconductivity, magnetism and other target properties can be obtained by rotating new materials such as graphene.

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In his theoretical model published in 2011, Canadian Allan MacDonald predicted that by twisting two graphene layers at a given angle, in the region of one degree, the interaction of electrons would produce new emerging properties. Seven years later, Spaniard Jarillo-Herrero and his team provided the experimental confirmation, fabricating bilayers of graphene rotated at this "magic angle" that transformed the material's behavior, giving rise to new properties like superconductivity.

"Their work has opened up new frontiers in physics by demonstrating that rotating matter to a given angle allows us to control its behavior, obtaining properties that could have a major industrial impact," explained committee member María José García Borge, a Research Professor at the Institute for the Structure of Matter (IEM-CSIC). "Superconductivity, for example, could bring about far more sustainable electricity transmission, with virtually no energy loss."

"The two men's joint contributions have defined a vast new field for developing materials with highly sought-after, emerging properties, and set the agenda for research groups across the world," added Luis Viña, Professor of Condensed Matter Physics at the Universidad Autónoma de Madrid and President of the Spanish Royal Physics Society, one of the nominators of the awardees. "MacDonald, from the standpoint of theory, and Jarillo-Herrero, through experiment, have become the architects of a new cutting-edge technology for creating hitherto unknown states of matter with the power to unlock advances in superconductivity and the creation of new electronic devices, and guide the future path of quantum computing."

The properties of graphene, predicting the unexpected

Allan MacDonald's scientific fascination with two-dimensional materials and their extraordinary physical properties first gripped him during a stay at the Max Planck Institute for Solid State Research, where he worked with Klaus von Klitzing (Nobel Prize in Physics in 1985). At the time, the illustrious German physicist's lab was trying to create materials that could further their study of phenomena like superconductivity. "The vision they had was to make these artificial materials they could manipulate at will," said the laureate in an interview shortly after hearing of the award. "But with the methods of the time they couldn't make them perfect enough, with the structure needed to see the really interesting things."

MacDonald was inspired by this vision to study unusual behaviors in stacked graphene sheets and, later, in other materials also formed by super-thin layers, seeking an entrance into a new world of properties with potential technological applications.

His research may be purely theoretical, but he is permanently on the lookout for results that can be translated to real-life situations, convinced of the need to find synergies between theory and experiment in the study of materials: “In twistronics, there is a hand and glove relationship between theory and experiment, like between the chicken and the egg. Theory is hugely important for experimentalists, because it points them toward which things are worth exploring. And experiments are a critical guide to theorists striving to understand the observed properties.”

In 2011, MacDonald predicted an unusual property of graphene, a material composed of a single layer of carbon atoms. By his calculations, on rotating one graphene sheet on top of another to a very precise angle, the electrons (which in conventional materials move at thousands of kilometers per second) would lose velocity, coming practically to a standstill. This dramatic slowdown raised the possibility of huge changes in the graphene’s behavior of a nature MacDonald could barely imagine when his results first appeared in the *Proceedings of the National Academy of Sciences*. The researcher gave the name of “magic angle” to this 1.1º misfit between the graphene layers.

An experimental validation from the realms of “science fiction”

The discovery, however, had little immediate impact, and it was not until some years later, when it was confirmed in the laboratory, that its true importance was revealed.

“The community would never have been so interested in my subject, if there hadn’t been an experimental program that realized that original vision,” observes MacDonald, who refers to his co-laureate’s achievement as “almost science fiction.”

Jarillo-Herrero, in effect, had been intrigued by the possible effects of placing two graphene sheets on top of each other with a precise rotational alignment, because “it was uncharted territory, beyond the reach of the physics of the past, so was bound to produce some interesting results.” But the scientist was still unsure of how to make it work in the lab. For years, he had been stacking together layers of this super-thin material, but without being able to specify the angle between them. Finally, he devised a way to control the misfit, making it smaller and smaller until he got to the “magic” angle of 1.1º at which the graphene revealed some extraordinary behavior.

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"It was a big surprise, because the technique we used, though conceptually straightforward, was hard to pull off in the lab. We took a sheet, made of something like transparent kitchen wrap but a hundred thousand times thinner than a hair. We cut it into two pieces and, taking care to avoid wrinkles, placed one on top of the other so they were perfectly aligned."

Writing up his results in two *Nature* papers of 2018, Jarillo-Herrero described how magic-angle graphene can become either insulating or superconducting, and that it is possible to tune its behavior with unprecedented predictability. His contribution became the most cited of the year in all areas of knowledge, not just in *Nature* but in all the journals within its publishing group. With the technique his team developed, layers of two-dimensional materials can now be stacked at any chosen angle, giving rise to all kinds of novel properties.

The potential for using graphene to reproduce any property of matter

For the awardees, the impact of this discovery has only just begun. "By rotating superimposed layers of two-dimensional materials at different angles, we can realize every possible behavior of matter," says Jarillo-Herrero. "Not just insulators and superconductors but also magnetism and a whole host of other complex behaviors." Until lately, he points out, we needed different elements from the periodic table to observe such a wide range of properties, but now, with graphene, we can see them all in just one – carbon. This element, he reflects, has become a sort of "reverse philosopher's stone", where instead of turning any material into gold, we can make graphene take on the behavior of any other material.

But to bring all this knowledge to industrial applications, an essential first step is to find better ways to manufacture graphene layers with a specific twist angle. The current process is so artisanal that it takes weeks or even months to produce just one device. Those who carry out this task are "like medieval monks creating a manuscript," says Jarillo-Herrero. "We don't have a print shop where we can turn out thousands or millions of identical copies of the same device, and getting to that point will require a lot of research work in basic engineering. Though certainly the interest is there within the community."

Future advances in our understanding of how graphene can be tuned to produce different behaviors of matter will lead to new materials with never-before-seen properties. "Among the likelier applications – says MacDonald – are new types of devices to convert information between computers and fiber optic cables. The technology is promising, and these materials are the best candidates for controlling optical properties electrically." An eventual "print shop" of graphene sheets rotated to different angles will allow us to verify the predicted usefulness of these materials for quantum technologies like computing and sensors, and certain types of artificial intelligence, at a much lower energy cost.

Laureate bio notes

Allan H. MacDonald (Antigonish, Nova Scotia, Canada, 1951) holds a BSc in Physics from St. Francis Xavier University (Nova Scotia, Canada) and an MSc and PhD on the same subject from the University of Toronto. During his time as a postdoctoral researcher and research scientist at the National Research Council Canada in Ottawa (1978 to 1987), he spent a year as a visiting scientist at the Swiss Federal Institute of Technology in Zurich (ETH Zurich), Switzerland. In 1988, he worked in an advisory capacity at the Max Planck Institute for Solid State Research in Stuttgart (Germany). A Professor of Physics at Indiana University (United States) between 1987 and 2000, he next joined the faculty of The University of Texas at Austin, where he holds the Sid W. Richardson Chair in Physics. His research has resulted in over 1,000 publications with some 110,000 citations, as well as three granted patents. A member of the Condensed Matter Division executive committees of both the Canadian and the American Physical Society, he has also served on a number of advisory boards, including those of the Canadian Institute for Advanced Research and the Kavli Institute for Theoretical Physics.

Pablo Jarillo-Herrero (Valencia, Spain, 1976) completed a BSc in Physics at the University of Valencia (1999) and an MSc in Physics at the University of California, San Diego (2001), before going on to earn a PhD at Delft University of Technology (Netherlands) in 2005. After working as a Nano Research Initiative Fellow at Columbia University (United States), in 2008 he joined the Massachusetts Institute of Technology, where he now holds the Cecil and Ida Green Chair in Physics. With over 160 publications to his name, he has been listed as a Highly Cited Researcher (Clarivate Analytics-Web of Science) uninterruptedly since 2017. Jarillo-Herrero has delivered over 300 lectures, holds four patents, and is a Distinguished Visiting Professor at ICFO - The Institute of Photonic Sciences (Barcelona, Spain). Among his other positions at MIT, he is Co-Director of the MIT Quantum Initiative, Associate Director of the Research Laboratory for Electronics, and a member of the Executive Committee of the Center for the Advancement of Topological Semimetals. He is also the founder and organizer of Rising Stars in Physics Workshops, academic career workshops for women held at MIT, Stanford, Princeton, Berkeley, and Columbia.

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Nominators

A total of 98 nominations including 106 candidates were received in this edition. The awardee researchers were nominated by Deepto Chakrabarty, Professor and Head of the Department of Physics at the Massachusetts Institute of Technology (United States); Kees Eijkel, General Director at QuTech (Delft University of Technology, the Netherlands); ICFO - The Institute of Photonic Sciences (Barcelona, España), through its Director, Oriol Romero-Isart, and Robert Sewell, Vice-Director of People, Education and Culture; Pablo Laguna, Professor and Chair of the Department of Physics at The University of Texas at Austin (United States); and the Spanish Royal Physics Society through its President, Luis Viña.

Basic Sciences committee and evaluation support panel

The committee in this category was chaired by **Theodor Hänsch**, Emeritus Director of the Division of Laser Spectroscopy at the Max Planck Institute of Quantum Optics (Germany) and the 2005 Nobel Laureate in Physics, with **Aitziber López Cortajarena,** Ikerbasque Research Professor, Scientific Director and Biomolecular Nanotechnology Group Leader at CIC biomaGUNE, Center for Cooperative Research in Biomaterials (Spain)**,** acting as secretary.

Remaining members were **Emmanuel Candès**, Barnum-Simons Professor of Mathematics and Statistics at Stanford University (United States); **María José García Borge**, Research Professor at the Institute for the Structure of Matter (IEM), CSIC (Spain): **Nigel Hitchin**, Emeritus Savilian Professor of Geometry in the Mathematical Institute at the University of Oxford (United Kingdom); **Martin Quack**, Professor and Head of the Molecular Kinetics and Spectroscopy Group at ETH Zurich (Switzerland); and **Sandip Tiwari**, Charles N. Mellowes Professor in Engineering, Emeritus at Cornell University (United States) and Distinguished Visiting Professor at the Indian Institute of Technology, Kanpur (India).

The **evaluation support panel** charged with nominee pre-evaluation was coordinated by **Dr. Elena Cartea**, Deputy Vice-President of Scientific-Technical Areas at the Spanish National Research Council (CSIC) and organized into three groups. The Physics Group was coordinated by **María Soledad Martín González**, Research Professor at the Institute of Micro and Nanotechnology of Madrid (IMN-CMN, CSIC), and formed by **Alberto Casas González**, Research Professor at the Institute for Theoretical Physics (IFT, CSIC-UAM); **Pere Colet Rafecas**, Research Professor at the Institute for Cross-Disciplinary Physics and Complex Systems (IFISC, CSIC-UIB); **Lourdes Fábrega Sánchez**, Tenured Scientist at the Institute of

Materials Science of Barcelona (ICMAB, CSIC); **Carmen García García**, Research Professor at the Institute of Corpuscular Physics (CSIC-UV); and **Alejandro Luque Estepa**, Tenured Scientist at the Institute of Astrophysics of Andalusia (IAA, CSIC). The Chemistry Group was coordinated by **José M. Mato**, General Director of CIC bioGUNE and CIC biomaGUNE, and formed by **Miguel Ángel Bañares González**, Research Professor at the Institute of Catalysis and Petrochemistry (ICP, CSIC); **Antonio Chica Lara**, Coordinator of the CSIC's 'Materia' Global Area and Scientific Researcher at the Institute of Chemical Technology (ITQ, CSIC-UPV); **Ethel Eljarrat Essebag**, Scientific Researcher and Director of the Institute of Environmental Assessment and Water Research (IDAEA, CSIC); **Jesús Jiménez-Barbero**, Scientific Director of CIC bioGUNE and Ikerbasque Research Professor in the Chemical Glycobiology Lab; **Gonzalo Jiménez-Osés**, Principal Investigator in the Computational Chemistry Lab at CIC bioGUNE; **Luis Liz-Marzán**, Principal Investigator in the Bionanoplasmonics Lab at CIC biomaGUNE; **Aitziber López Cortajarena**, Ikerbasque Research Professor, Scientific Director and Principal Investigator in the Biomolecular Nanotechnology Lab at CIC biomaGUNE; and **María Luz Sanz Murias**, Scientific Researcher and Deputy Director at the Institute of General Organic Chemistry (IQOG, CSIC). The Mathematics Group was coordinated by **José María Martell Berrocal**, CSIC Research Professor and the Council's Vice-President for Scientific and Technical Research, and formed by **María Jesús Carro Rosell**, Professor of Mathematical Analysis at the Complutense University of Madrid (UCM); **Alberto Enciso Carrasco**, Research Professor at the Institute of Mathematical Sciences (ICMAT, CSIC); **Francisco Martín Serrano**, Professor of Differential Geometry at the University of Granada; and **Rosa María Miró Roig**, Professor of Algebra at the University of Barcelona.

About the BBVA Foundation Frontiers of Knowledge Awards

The BBVA Foundation centers its activity on the promotion of world-class scientific research and cultural creation, and the recognition of talent.

The BBVA Foundation Frontiers of Knowledge Awards, funded with 400,000 euros in each of their eight categories, recognize and reward contributions of singular impact in basic sciences, biomedicine, environmental sciences and climate change, information and communication technologies, social sciences, economics, humanities and music. The goal of the awards, established in 2008, is to celebrate and promote the value of knowledge as a global public good, the best tool at our command to confront the defining challenges of our time and expand individual worldviews. Their eight categories are congruent with the knowledge map of the 21st century.

The BBVA Foundation is partnered in these awards by the Spanish National Research Council (CSIC), the country's premier public research organization. CSIC appoints evaluation support panels made up of leading experts in the corresponding knowledge area, who are charged with undertaking an initial assessment of candidates and drawing up a reasoned shortlist for the consideration of the award committees. CSIC is also responsible for designating each committee's chair across the eight prize categories and participates in the selection of remaining members, helping to ensure objectivity in the recognition of innovation and scientific excellence. The presidency of CSIC also has a prominent role in the awards ceremony held each year in Bilbao, the permanent home of the BBVA Foundation Frontiers of Knowledge Awards.

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