

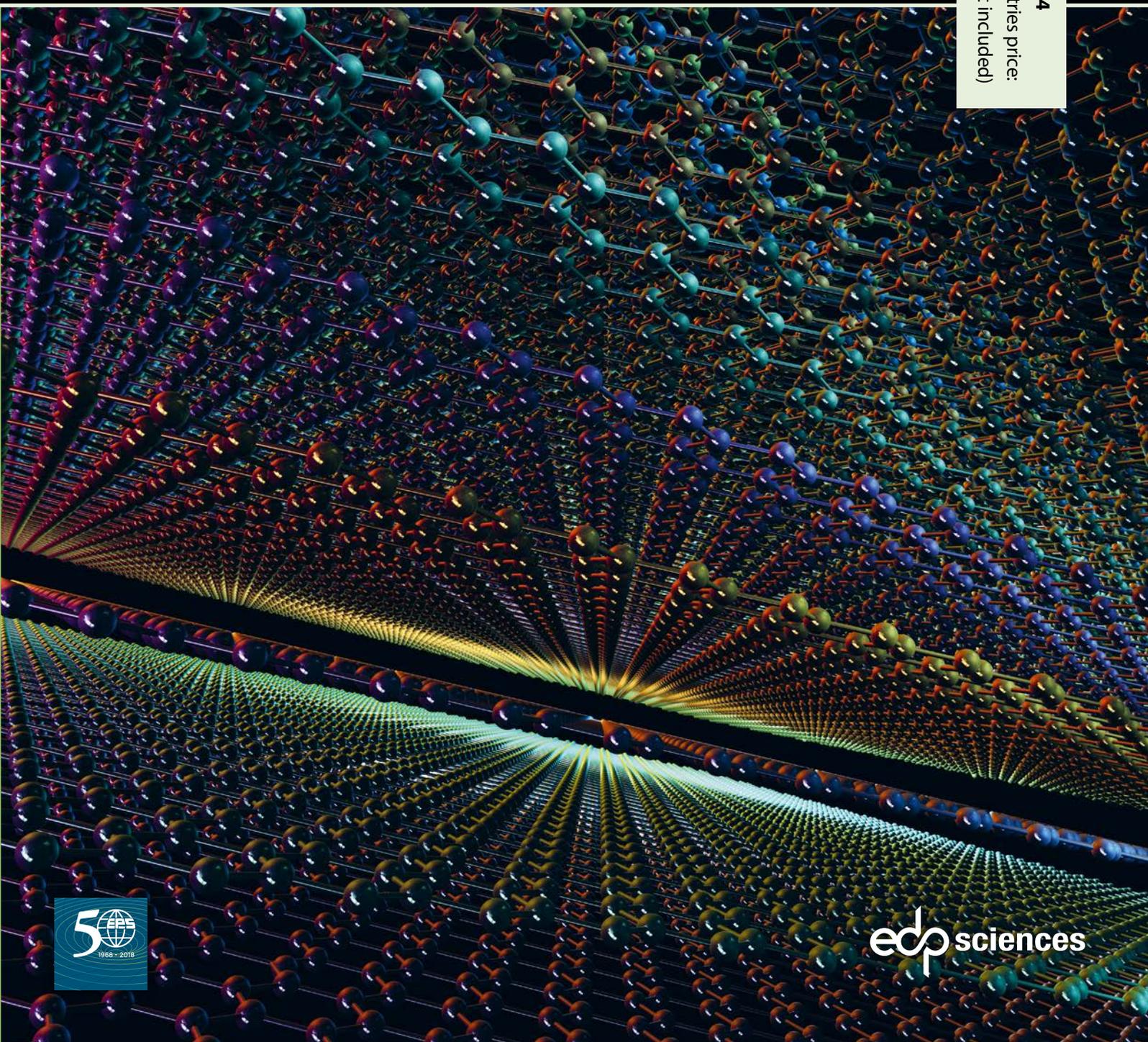
# europhysicsnews

THE MAGAZINE OF THE EUROPEAN PHYSICAL SOCIETY

**Topological insulators**  
**The hidden patterns of dipolar near fields**  
**How polyethene came about**  
**A new perspective on new materials**  
**A tribute to Max Planck**

**49/4**  
**2018**

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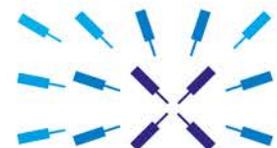
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### Typical Applications

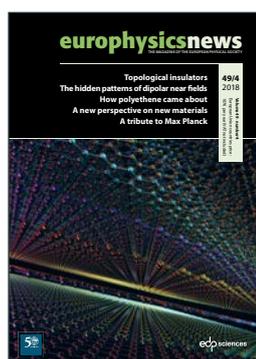
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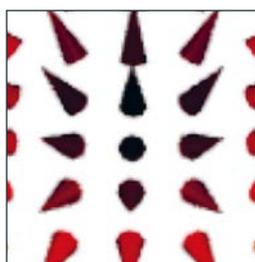


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# europhysicsnews

**Cover picture:** Graphite draps © iStockPhoto.  
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[EDITORIAL]

## No Section is an island future perspectives for the Young Minds project

**Young Minds (YM) is a project developed by European Physical Society (EPS) in order to involve students and young physicists in EPS activities, by fostering self-organized student groups called Sections, running student-led projects.**

Since its very beginning, YM activities were based on three pillars: outreach, professional development and networking. Outreach activities are aimed at science diffusion and science popularization: not only science fairs and festivals, but also crash courses for high school students, masterclasses, and public seminars. On the other hand, technical seminars, workshops and conferences are labelled as professional development activities, since they are aimed at the professional growth of YM members. Both types of activities can be seen as networking activities, even though networking is not limited to this: on one side, we aim at building a connection between science and society, on the other, we invest in the creation of bonds between scientists coming from different countries and different backgrounds.

I have been part of the project since its very beginning in 2010. At the time, I was a bachelor student in Naples, and I was literally fascinated by the range of opportunities that YM was disclosing to me, so I was among the few students who founded the local EPS Young Minds Naples Section. My academic career developed side by side with my path in YM. It was not an accident, but rather a deliberate choice, because since the very early stages of my career I felt the need to perceive the utility for the community of what I was studying, and the student-oriented initiatives of YM provided space and means to

achieve it. Now that I finished my PhD, I embarked on the adventure of being the chair of the YM project, starting from last May. It's been a long journey so far, but certainly it was all worth it, as YM taught me the meaning of being part of a European community. The second big lesson I learned from being part of such a network, is how crucial it is to learn to find time to dedicate to what makes you feel passionate: in my case it was science communication.

Eight years after its beginning, the Young Minds project counts 52 sections in 23 countries: it has now reached the critical mass to become a reference point at the European level in the student network panorama. Up to now, the main target of the project has been growth. Now, we need to change our perspective a little bit and focus on the relationships between sections themselves, parent universities and research centers, EPS and European institutions.

In order to build the next generation of scientists, society has to invest not only in academic education,

**To build the next generation of scientists, society has to invest not only in academic education, but also in the creation of a network of people sharing the same goals and objectives.**

▼ Picture of the YM Leadership Meeting in Prague, May 4<sup>th</sup> and 5<sup>th</sup>, 2018



but also in the creation of a network of people sharing the same goals and objectives. Indeed, this will be the target of the Young Minds project in the next two years: working to establish a network of local student Sections that can cooperate and evolve on a common ground. As part of the European Physical Society, the Young Minds are committed to achieve the targeted scope within a European framework, taking advantage of all the opportunities that this provides. As an example, one of our mid-term goals will be to increase the active participation of people from YM network in EPS conferences with activities specifically oriented to young professionals. We also plan in the long term to coordinate the participation of the sections in European events such as the Researchers Night or the International Day of Light, and eventually start our own events, following the example provided by other successful networks.

If we wish to face the challenges of our times as young scientists, we need to strengthen our collaboration and enforce the idea that only if we work together we can increase the awareness of the importance of science in society. After all, the most important lesson I learned from Young Minds is that “No man is an island, entire of itself”, and even more so, no Section is an island. ■

■ **Roberta Caruso,**  
*University of Naples Federico II*

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# EPS Council 2018

## 6-7 April - Paris, France

**The annual Council Meeting of the European Physical Society was held on 6-7 April 2018 at Jussieu Campus (formerly the Université de Pierre et Marie Curie) of the Sorbonne Université. The EPS Council is composed of representatives of the 42 EPS Member Societies and the chairpersons of the 12 Divisions, 6 Groups, and 6 Committees. Individual Members and Associate Members are each represented by 5 elected delegates.**

The Council meets for a variety of reasons. There are extensive reports, covering the activities and finances of the previous year. (The annual report can be downloaded here: [https://www.eps.org/global\\_engine/download.asp?fileid=2B2DC642-7F8F-4BB9-A885-BE8DC45B5C8A&ext=pdf](https://www.eps.org/global_engine/download.asp?fileid=2B2DC642-7F8F-4BB9-A885-BE8DC45B5C8A&ext=pdf).)

Conferences are an activity where the EPS is highly successful. Our Divisions and Groups organise many of the most important and prestigious meetings in Europe, often drawing a global audience. Following a recommendation from the Conference Committee, a simplification has been introduced in 2017: whereas the established “Europhysics Conference” label will be maintained, all high-quality meetings or workshops to which the EPS can offer only limited support will in future be grouped under the label “EPS Recognised Conference”.

The **Young Minds Project** continues as a successful programme of the EPS to support and federate the young generation of scientists which represents the future of our field, with a special emphasis on outreach activities and cross-border networking. The basic organisational units of the YM Project are local Sections, which have increased in number from 40 to 49 in 2017, now representing 23 different countries – one of the greatest increments since the project was started in 2010.

The **Equal Opportunities Committee** has initiated a new Gender Monitoring Programme for EPS supported conferences which, in the medium term, is expected to lead us to more formal policies to ensure a fair representation of women physicists at our meetings. Another, well-established action to promote the visibility and career of outstanding female scientists is the Emmy Noether Distinction, which in 2017 has been awarded to Catalina Curcanu and Françoise Remacle.

The **Committee on European Integration** (CEI) continues to address the issues related to the uneven distribution of research and funding opportunities across Europe, and disparities persist between East and West through the strengthening of regional co-operation between Eastern, Central, and South-East European countries, and with other Member Societies. In the same spirit, the EPS supports the new initiative for a South East Europe International Institute for Sustainable Technologies (SEEIST).

The EPS will celebrate an important milestone in 2018: on September 28, it will be 50 years that our society was formally launched with a ceremony in the Aula Magna of the University of Geneva. All EPS stakeholders are encouraged to set aside time in their meetings, and space in their publications,

to celebrate 50 years of EPS and to promote the mission and activities of our society.

## EPS Elections 2018

**Petra Rudolf** is the next EPS President-elect. She will take up office as the President of EPS in April 2019, when the term of the current President, **Rüdiger Voss**, comes to an end. He will serve a further term as EPS Vice-President.

In addition to the EPS President-elect, the EPS elected the **members of the Executive Committee**: Rüdiger Voss (CERN Emeritus Staff Member) remains the EPS President. Below, please find the list of the members of the Executive Committee. *Those that have been elected for a second and final term are shown with “\*” after their name.*

Luc Bergé \* (FR), Ursel Fantz (DE), Sylvie Jacquemot \*(FR), Eugenio Nappi (IT), Teresa Peña (PT), Eliezer Rabinovici (IL), Frances Saunders (UK), Quang Minh Tran \*(CH), Victor Zadkov (RU), Victor Zamfir \*(RO), Gertrud Zwicknagl (DE).

The EPS would like to thank the outgoing members of the Executive Committee for their hard work and dedication: Siegfried Bethke, Angela Bracco, Lucia di Ciaccio, Ari Friberg, Gerd Leuchs, and Elizabeth Rachlew. A special thanks was extended to the outgoing Immediate Past President, Christophe Rossel, who has made exceptional contributions over his term as President, and continues as the chair of the EPS 50<sup>th</sup> Anniversary celebrations.

## EPS distinctions 2018

The following individuals have been awarded **Honorary Membership** of the European Physical Society:

**Professor Pedro Miguel Echenique**, President of the Donostia International Physics Center (DIPC), has been awarded Honorary Membership of the European Physical Society at the Council 2018 in Paris for his outstanding achievements as a scientist in the field of Surface Physics, Attophysics,



▲ View from the Campus Jussieu, April 2018

Interaction of charges and radiation with matter and Many-body Physics and for his contributions as an exceptional and tireless advocate of outreach, dissemination and public awareness of physics, notably the creation and development of Passion for Knowledge, which is a large-scale public outreach event in Donostia, Basque Country, promoting science as the driving force behind technological progress and the foundation of human culture.

**Professor Luciano Maiani**, Chairman of the Scientific Council of the International Centre for Theoretical Physics, former CERN Director General, has been awarded Honorary Membership of the European Physical Society at the Council 2018 in Paris for his exceptional scientific contributions to elementary particle physics and outstanding achievements in the leadership of Italian and International Scientific institutions.

The following individuals were elected as **Fellows** of the EPS:

**Herzl Aharoni** for his ground breaking contributions and accomplishments in the invention, research, development, and realisation of wide range of practical, cost-effective, efficient, single crystal Silicon Light Emitting Devices and by pioneering a systematic transformation of physics into technology.

**Els de Wolf** for her outstanding contributions to both fundamental and

applied physics, to the EPS, to the NNV, to education and to the society at large.

The 2018 European Physical Society **Gero Thomas Medal** is awarded to: **Angela Oleandri** for her outstanding and sustained contributions to the development of physics publications in Europe, including her support to the creation and development of the EPJ series of journals and EPL (Europhysics Letters).

The 2018 European Physical Society **Achievement Award** is awarded to: **Giorgio Benedek** for his numerous contributions to the European Physical Society, the physics community at large, and most recently for his truly outstanding efforts as Editor-in-Chief of EPL.

Finally, the EPS Council delegates listened to an entertaining and informative talk by Metin Tolan, Professor of Physics at the University of Dortmund (DE) on the physics in James Bond movies. The title “Shaken, not stirred” refers to the preferred method of the fictional British spy of mixing a martini.

The EPS would like to thank Sylvie Jacquemot and Dominique Vernhet and the staff of the Jussieu Campus of Sorbonne Université for their assistance in making the EPS Council Meeting in 2018 a memorable experience. ■

**David Lee**  
EPS Secretary General

# Highlights from European journals

## COMPLEX SYSTEMS

### Rush hour metro crowd governed by people's eagerness to go home

**New model examines the relative role of random interactions between individuals in a crowd compared to interactions stemming from their eagerness to be on their way.**

Ever found yourself crushed in a metro station at rush hour? The authors have developed a new model to study the movement of crowds exiting a metro station. In a recent study they have for the first time employed models typically used to study gases consisting of a large number of molecules that collide at random (known as thermostatted kinetic theory) to study the consequences of the different interactions occurring among pedestrians in a crowd while exiting a metro station. The authors assume that what motivates pedestrians to leave a metro station can be modelled as an external force that explains the conditions under which they leave due to the crowd pressure. Their model combines aspects representing the interactions between pedestrians and governed by thermostatted kinetic theory with the cooperation between pedestrians as intelligent and self-organised decision-makers, which is governed by game theory. Numerical simulations on the magnitude of the external force explain how internal interactions between pedestrians can be affected by an external force driving them to leave the station. What matters most is that all of the pedestrians are individually in the same hurry to exit the station and get away from the crowd. ■

■ **C. Bianca, and C. Mogno,**

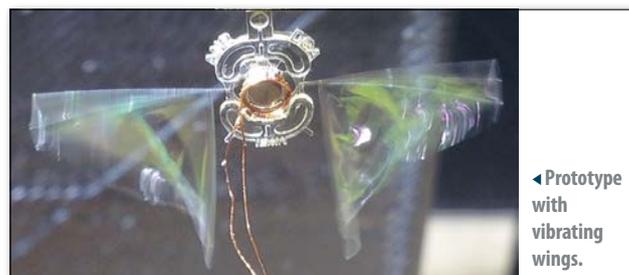
'A thermostatted kinetic theory model for event-driven pedestrian dynamics', *Eur. Phys. J. Plus* **133**, 213 (2018)

▼ Rush hour crowd governed by people's eagerness to go home.  
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## APPLIED PHYSICS

### Insect-like vibrating winged NAV



◀ Prototype with vibrating wings.

This work presents an original concept using the combination of two resonant vibration modes of the flexible wings of a Nano-Air Vehicle to reproduce insect wings kinematics and generate lift. Since insects use for flying a kinematics which combines flapping and twisting motions with a specific phase shift, the main goal of this study is to design the artificial wings such that they feature two vibration modes which are producing flapping and twisting deformations and to combine them with the appropriate phase shift. For this purpose, a polymeric prototype was micromachined with a wingspan of 3 cm, flexible wings and a single electromagnetic actuator as illustrated in the figure.

An optimal wings configuration was determined with a modelling and validated through experimental analyses to observe the vibrating behaviour of the prototype. A dedicated lift force measurement bench was then used to demonstrate a lift force equivalent to the prototype weight. Finally, at the maximum lift frequency, high-speed camera measurements confirmed a kinematics of the flexible wings with flapping and twisting motions combined in the expected phase shift. ■

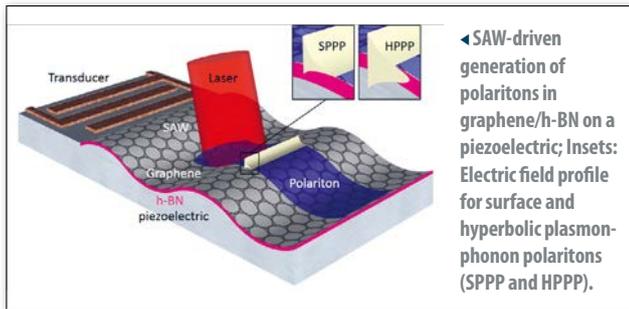
■ **D. Faux, O. Thomas, E. Cattani and S. Grondel,**

'Two modes resonant combined motion for insect wings kinematics reproduction and lift generation', *EPL* **121**, 66001 (2018)

## APPLIED PHYSICS

### Nanoscale light trapping in graphene/h-BN by sound waves

Graphene plasmonics is a rapidly emerging field exploiting the extreme light confinement provided by the 2D nature of graphene that results in enhanced light-matter interaction. However, a large momentum mismatch needs to be overcome by a photon to couple with a plasmon into a plasmon



polariton. In this work, the authors have demonstrated a unique way for exciting polaritons in graphene/h-BN systems on a piezoelectric material by using a surface acoustic wave (SAW) generated by an integrated transducer. The SAW acts as a virtual diffraction grating providing the extra momentum needed to generate propagating polaritons using a simple laser. h-BN is widely used as an ideal substrate for graphene providing it with very high mobility. Moreover, h-BN is a natural hyperbolic insulator (*i.e.* the dielectric function has opposite sign in the two reststrahlen bands), where graphene plasmons couple strongly to both surface and hyperbolic (waveguided) phonons in h-BN, leading to hybridized surface and hyperbolic plasmon-phonon polaritons. These results pave the way for engineering SAW-driven graphene/h-BN plasmonic devices and metamaterials covering the mid-IR to THz range. ■

■ **R. Fandan, J. Pedrós, J. Schiefele, A. Boscá, J. Martínez and F. Calle,**

'Acoustically-driven surface and hyperbolic plasmon-phonon polaritons in graphene/h-BN heterostructures on piezoelectric substrates', *J. Phys. D: Appl. Phys.* **51**, 204004 (2018)

## NUCLEAR PHYSICS

### The Soreq Applied Research Accelerator Facility (SARAF)

The Soreq Applied Research Accelerator Facility (SARAF) is under construction in the Soreq Nuclear Research Center at Yavne, Israel. Phase I of SARAF (SARAF-I) is already in operation, generating scientific results in several fields of interest, especially the astrophysical s-process. When completed at the beginning of the next decade, SARAF-II will be a user facility for basic and applied nuclear physics, based on a 40 MeV, 5 mA CW proton/deuteron superconducting linear accelerator. This review presents first a technical overview of SARAF-I and II, including a description of the accelerator and its irradiation targets, and provides a survey of existing research programs at SARAF-I. It then describes in some detail the research potential at the completed facility. SARAF-II's cutting-edge specifications, with its unique liquid lithium target technology, will enable world-competitive research plans in several disciplines: precision studies of beyond-Standard-Model effects by trapping light exotic radioisotopes (including meaningful studies

already at SARAF-I); extended nuclear astrophysics research with higher-energy neutrons, including generation and studies of exotic neutron-rich isotopes relevant to the astrophysical r-process; nuclear structure of exotic isotopes; high-energy neutron cross sections for basic nuclear physics and material science research, including neutron-induced radiation damage; neutron-based imaging with an imaging plane flux similar to that of a 5 MW research reactor; accelerator-based neutron therapy; and, last but not least, novel radiopharmaceuticals development and production. ■

■ **I. Mardor and 28 co-authors,**

'The Soreq Applied Research Accelerator Facility (SARAF): Overview, research programs and future plans', *Eur. Phys. J. A* **54**, 91 (2018)

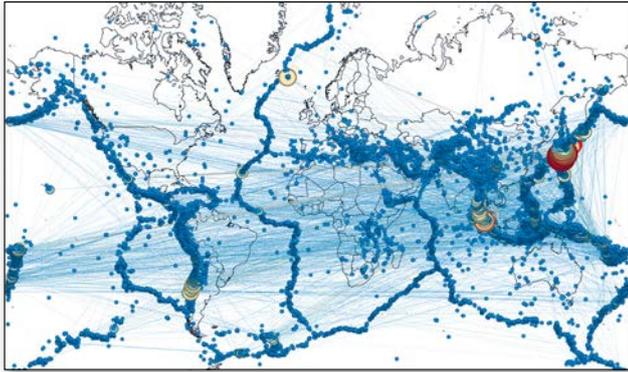
▼ Layout of SARAF, including the accelerator and the research areas.



## COMPLEX SYSTEMS

### Evidence of Long-range Correlations in Shallow Earthquakes

Earthquakes are one of the most devastating natural disasters by the number of casualties and the negative economic impact. Seismic phenomena have been studied from the viewpoint of complex systems, where complex patterns arise from nonlinear interactions between their elements. One of such ways is using networks of geographical sites; we introduce a new methodology to construct networks of epicentres and applied it to global catalogs of shallow earthquakes. It involves essentially the introduction of a time window, which works as a temporal filter for vertices connections. The resulting network constructed has small-world properties and presents scale-free properties in its connectivity distribution, which we proved to be invariant with respect to the value of the time window adopted. Vertices with larger connectivity in the network correspond to areas with very intense seismic activity in the period considered. These new results constitute



▲ Geospatial picture of the global network. We only show links occurring at least three times between the same two cells. The sites with largest cells (reddish and larger) are located around Japan, Sumatra Island, Chile and Iceland.

evidences of possible spatial and temporal long-range correlations between earthquakes. ■

■ **D. Ferreira, J. Ribeiro, A. Papa and R. Menezes,** 'Towards evidence of long-range correlations in shallow seismic activities', *EPL* 121, 58003 (2018)

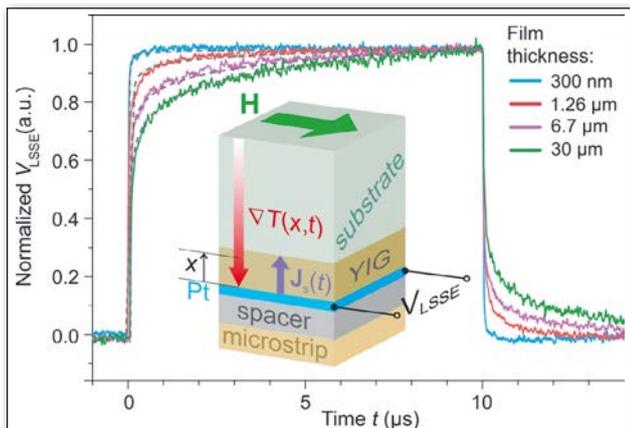
APPLIED PHYSICS

## Temperature-driven ballistic magnon transport

Application of a temperature gradient to a magnetic medium leads to the generation of a spin current referred to as the longitudinal spin Seebeck effect (LSSE). In a magnetic insulator such a current is created by a flux of thermal magnons. Using spin-dependent electron scattering processes in the adjacent normal metal this current can be converted to an electric voltage. The voltage evolution is determined by the development of the temperature gradient  $\nabla T(x,t)$  and by the characteristics of the magnon's motion.

By analysis of the time-dependent LSSE voltages in platinum-coated Yttrium Iron Garnet (YIG) ferrimagnetic films, the

▼ Temporal evolution of the spin Seebeck voltage  $V_{LSSE}$  for different magnetic film thicknesses. Inset: A platinum-coated magnetic insulator YIG subject to a thermal gradient created by microwave heating of the Pt layer. A thermally actuated magnon spin current  $J_s$  induces  $V_{LSSE}$ .



authors assumed that thermally-driven magnons with energies above 20 K move through the YIG layer *ballistically* due to their almost linear quasi-acoustic dispersion law. Consequently, the interaction processes within the 'acoustic' magnon mode do not change the magnon propagation velocity, while the number of magnons decays exponentially within an effective propagation length of 425nm. This length was found to be mostly independent of film thickness that proves the ballistic magnon transport scenario. ■

■ **T. B. Noack and eleven co-authors,** 'Phase-dependent noise in Josephson junctions', *Eur. Phys. J. Appl. Phys.* 81, 10601 (2018)

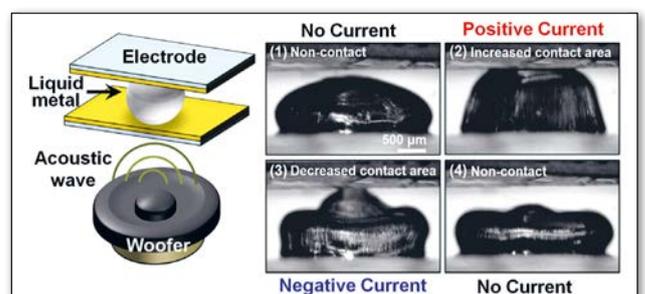
APPLIED PHYSICS

## Liquid Metal Energy Harvester by Acoustic Wave

We report an oxidized liquid metal droplet-based energy harvester that converts acoustic energy into electrical energy by modulating an electrical double layer that originates from the deformation of the oxidized liquid metal droplet. The proposed energy harvester consisted of top and bottom electrodes covered with a dielectric layer and a Gallium-based liquid metal droplet placed between the electrodes. When we applied an external bias voltage and an acoustic wave to the proposed device, the contact area between the liquid metal droplet and the electrodes changed, leading to the variation of the capacitance in the electrical double layer and the generation of electrical output current. Using the proposed energy harvester, a maximum output current of 41.2 nA was generated with an applied acoustic wave of 30 Hz. In addition, we studied the relationships between the maximum output current and a variety of factors, such as the size of the liquid metal droplet, the thickness of the hydrophobic layer, and the distance between the top and bottom electrode plates. ■

■ **J. Jeon, S. K. Chung, J.-B. Lee, S. Joo Doo and D. Kim,** 'Acoustic wave-driven oxidized liquid metal-based energy harvester', *Eur. Phys. J. Appl. Phys.* 81, 20902 (2018)

▼ Current generation by modulating the liquid metal shape with an applied acoustic wave.



# TOPOLOGICAL INSULATORS: HOW THE DEEP CONTROLS THE SUPERFICIAL

■ Janos K. Asboth, – DOI: <https://doi.org/10.1051/epr/2018401>

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**Topological insulators prevent current from passing through, but also ensure that it flows unimpeded from contact to contact on their surface. The combination of ideas from topology and band theory to explain and generalize this peculiar behaviour has had a transformative effect on condensed matter research.**

A simple explanation of why some solids conduct electricity and others are insulators, Bloch's *band theory* of electrical conduction, was one of the first triumphs of quantum mechanics. It forms the basis of the semiconductor industry, and fails only in surprisingly few cases. Focusing on the atoms in the bulk of the crystal, it predicts that a material is an insulator if it has an energy gap separating fully occupied bulk bands from fully empty ones.

Even band insulators can conduct electricity if, due to some special conditions, they have extended electronic states on their surface with energy in the bulk gap. Atoms on or near the surface have a different environment from those in the bulk, so the bulk energy gap does not exclude the possibility that orbitals of surface atoms hybridize and form a conducting layer. Such conduction is in most cases very sensitive to sample fabrication conditions, or to disorder, which through Anderson localization causes extended energy eigenstates of electrons on the surface to break up into small parts.

*Topological Insulators* [1-3] are band insulators which have robust conduction via surface states, a phenomenon that is linked to topological defects in the bulk Brillouin Zone. Topological insulators can be 2-dimensional, as is

the case in the Quantum Hall Effect, but also 3-dimensional with robust conducting surfaces, like BiSb alloys[4], or one-dimensional, like the Su-Schrieffer-Heeger model for polyacetylene[5]. Theoretical constructions exist for topological insulators in any dimensions, an example being the 4-dimensional Quantum Hall Effect[6], whose delocalized "surface" states are 3-dimensional.

## The first topological insulator: the quantum Hall effect

The first example for an insulator with surface states that ensure conduction is the Quantum Hall Effect (von Klitzing, 1980). Here, a two-dimensional semiconductor is turned insulating by a strong magnetic field that confines the motion of electrons in the bulk by the Lorentz force. At low enough temperatures, as the magnetic field is increased further, the sample turns conducting, then insulating, then conducting, and so on: it undergoes a sequence of phase transitions. In an insulating phase, even though the bulk does not conduct, there is a current flowing along the edges of the sample, in an integer number of one-way conducting quasi-1-dimensional channels, as shown in Fig. 1. The various insulating phases differ from each other in the number  $n$  of edge state channels

on each edge, which lead to a very precisely (9 significant digits) quantized value of Hall conductance:  $U_{\text{transverse}} = nI2e^2/h$ , as revealed by 4- and 6-terminal measurements.

Having a discrete integer associated to a bulk insulator hints at a topological invariant hiding behind surface state conduction in the Quantum Hall Effect. The explanation was given in the first years of the 1980's, and was part of the reason Thouless was awarded the Nobel prize in physics in 2016. Thouless *et al.* have shown[7] that the number of edge state channels, *i.e.*, open channels at the boundary of the sample, is given by the net number of topological defects (of the Berry connection) in the Brillouin Zone, counted by the first Chern number of the occupied bulk bands.

In the decades since the discovery of the Quantum Hall Effect more examples have been found where robust edge states appear in tandem with nontrivial bulk Brillouin-zone topology. Haldane (another of 2016's Nobel laureates) has shown using a toy model[8] that a net external magnetic field is not required. A large boost to this line of research was given by Kane and Mele [9] who have shown that these phenomena do not require any breaking of time-reversal symmetry, which was experimentally demonstrated[10,11] on a thin layer of HgTe.

**Topological invariants of band insulators**

The reason why some insulators are “topological” is that they have *topological invariants*. A topological invariant is an integer-valued property of the sample that cannot change under so-called adiabatic deformations: a continuous change of either the sample's shape or its parameters, with the bulk gap not closed, and the relevant symmetries respected. Topological invariants thus represent obstructions against adiabatically deforming the sample to an atomic insulator – a material that consists of disconnected unit cells. The topological invariants come in two flavours: those associated to the boundary of the sample and those associated to the bulk.

The boundary topological invariants of topological insulators quantify the robust physical properties of the surface of the sample. The invariant is essentially the number of protected surface states. For topological

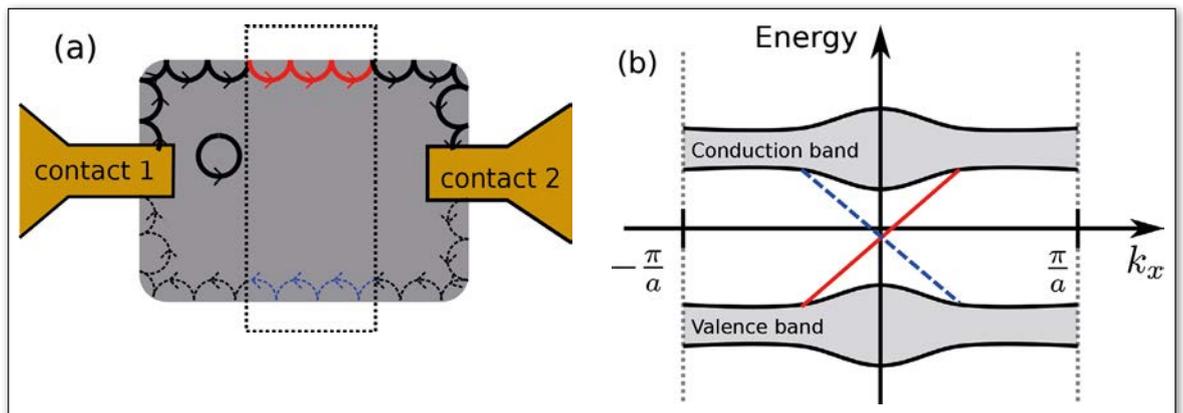
insulator wires, it is the number of edge states with protected energy, for two-dimensional topological insulators, the value of surface conductance in units of the conductance quantum, while in three-dimensional case, it is the number of Dirac cones on the surface. The surface states are *topologically protected* in the sense that their number (or other properties specified by the invariant) cannot change under adiabatic deformations. Topologically protected surface states constitute an obstruction against adiabatic deformation to an atomic insulator, since in atomic insulators the surface is no different from the bulk, and so they cannot host surface states in the bulk gap.

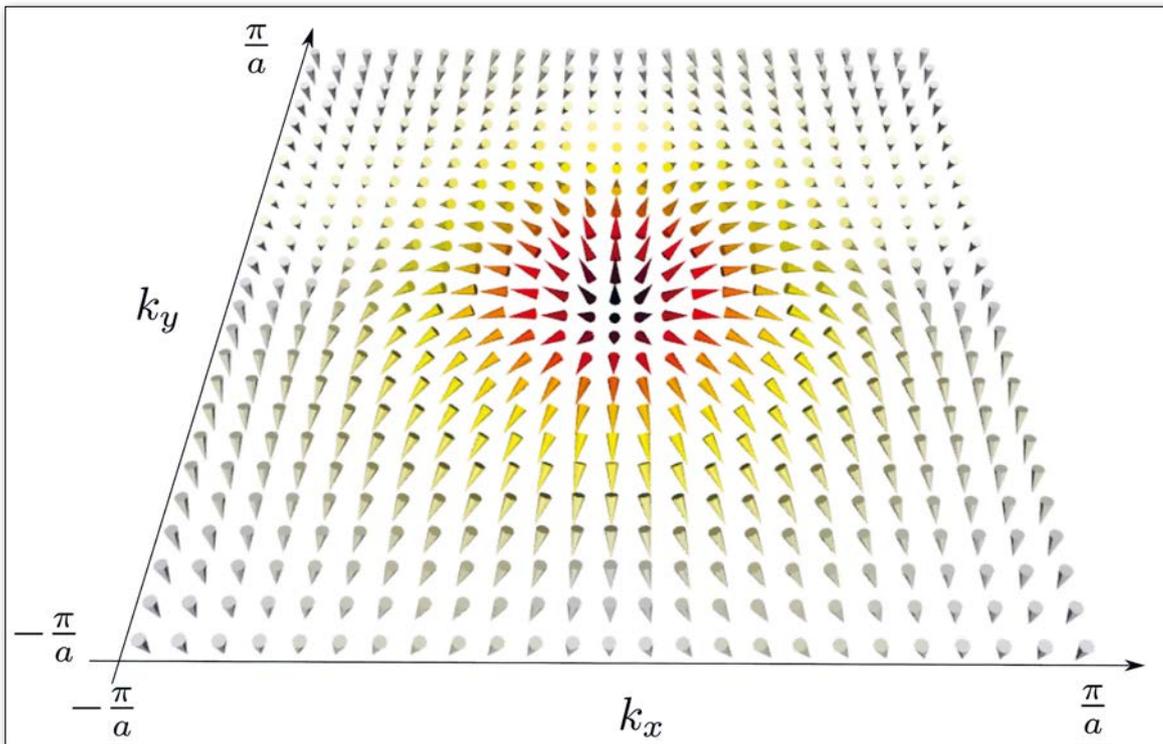
The bulk topological invariants are easiest to define for disorder-free, noninteracting systems, where they can be accessed through the description of the energy bands. Each energy band is a mapping from the toroidal Brillouin Zone to the internal Hilbert space, since each plane-wave energy eigenstate not only has an energy but also some orbital and spin structure. This mapping is smooth, but can have topological defects, which can present obstructions to smoothly connect the mapping to the trivial mapping, *i.e.*, where all plane waves in the band have the same orbital structure, corresponding to the atomic insulator. It is the number of these topological defects, *e.g.*, twists, vortices, skyrmions, of some function of occupied bands over the Brillouin Zone, that is the topological invariant of the bulk – for an example, see Fig. 2. When the bulk is disordered, defining its topological invariants becomes more tricky, and can be done, *e.g.*, using suitably defined scattering matrices[12].

**Bulk–boundary correspondence**

The two invariants of topological insulators, that of the surface, and that of the bulk, are connected by the bulk–boundary correspondence, which is at the heart of the theory of topological insulators. For the Quantum Hall Effect, this correspondence is the finding of Thouless that the net number of edge state channels is given by the Chern number of the bulk. This type of connection persists for topological insulators of any dimension or symmetry class, *e.g.*, between the number of topologically protected edge state channels and the bulk  $Z_2$  invariant in time-reversal invariant two-dimensional

► FIG 1: In a Quantum Hall insulator, electrons can carry current from contact to contact (a) even though they cannot pass through the bulk, by bouncing along the edge. The states on the edge form discrete channels, which can be revealed by the dispersion relation (b) of a part of the sample with translation invariance along x (dotted rectangle in (a)). Energy eigenstates localized near the upper (red) and lower (blue) edge of the sample form branches of the dispersion relation, and show that propagation along each edge is in one direction only.





◀ **FIG 2:** A topological defect, a skyrmion in the Brillouin zone of a two-band toy model for a topological Chern Insulator (Qi-Wu-Zhang model, with  $u=1.5$  using the notation of [13]). The arrows are vectors on the Bloch sphere, representing the orbital structure of the occupied band. Bearing in mind the periodic boundary conditions, there is no smooth deformation of this field into a trivial one, corresponding to an atomic insulator, where all arrows face in the same direction. (Source: László Oroszlány).

topological insulators, or the bulk sublattice polarization and the number of edge states in the Su–Schrieffer–Heeger model for polyacetylene. Bulk–boundary correspondence is often loosely stated as a topological phase transition in space. Since there is no way to adiabatically deform insulators with different bulk topological invariants into each other, at a smooth interface between them, where the parameters are varied slowly in space, the bulk gap must close and hence there have to be edge states. Nevertheless, turning this loose argument into a precise statement is not straightforward, as bulk–boundary correspondence should apply to the physical edges of the material (boundaries with vacuum) as well as to interfaces where the spatial variation of the parameters is abrupt. Thus, bulk–boundary correspondence becomes a deep statement, requiring more complicated tools, such as connecting charge pumping with edge states [13], and whose rigorous proof is ongoing work.

### Topological superconductors, and the full classification

Superconductors can also display the bulk–boundary correspondence characteristic of topological insulators, if instead of the electric charge, one considers more general single-particle excitations. Although an electron can travel across a superconductor, it can only do so by taking another electron with it with which it can form a Cooper pair. In a mean-field picture this happens via a so-called Andreev reflection, where an incident electron is reflected as a hole. A superconductor is then described in an extended space of electrons and holes as a band insulator, by the so-called Bogoliubov–de Gennes Hamiltonian. Bulk topological invariants can then be associated to superconductors from the energy bands of the Bogoliubov–de Gennes

Hamiltonian (or using the scattering matrices or other approaches). The corresponding topologically protected surface states are electron–hole superpositions, which have a close analogy with Majorana fermions [14]. Such solid-state Majorana fermions can be created and manipulated in semiconducting quantum wires proximitized by ordinary superconductors. Because of the topological protection of the energies of these states, they are seen as a promising path for building a quantum computer [15].

The complete classification of universality classes of topological insulators and superconductors [16–18] was one of the milestones of condensed matter theory in the previous decade. For band insulators of any dimensions it has been identified what combination of nonspatial symmetries (time-reversal, particle–hole, or chiral symmetry) are required the system to be a topological insulator. Derivations of the classification use dimensional extension/reduction [12, 16–18] to connect topological insulators of different dimensionality. Because the requirements follow an 8-dimensional periodicity, the classification is known as the *periodic table of topological insulators*.

### Extensions of the field of topological insulators

An actively researched extension of the field of topological insulators is topological semimetals [19]. These are zero-gap semiconductors where the conduction and valence bands touch each other at topologically protected, isolated points (or lower dimensional manifolds) of degeneracy in the Brillouin zone. To see that the degeneracies in such materials are protected, one calculates the topological invariant associated to a closed surface in the Brillouin zone that encloses the degeneracy. If the invariant is nonzero, then it

represents an obstruction to a local adiabatic deformation of the system that would separate the two bands. Around the degeneracy points the dispersion relation is linear, and such materials host analogues of Weyl fermions in the same way as topological superconductors do for Majorana fermions.

Another direction in which the field of topological insulators is pushed is to incorporate spatial symmetries, such as inversion, or rotation. So-called crystalline insulators are materials whose topological invariants depend crucially on such symmetries. They host topologically protected surface states only on surfaces that are aligned with the crystallographic axes so that the important spatial symmetries are respected. Incorporating the various types of symmetries to produce greater and greater periodic tables of topological crystalline insulators is ongoing work[3].

Floquet topological insulators[20] are periodically driven systems that can host edge states even if all of their bulk bands have trivial topology. Periodic driving, or the “shaking of the lattice” on timescale much shorter than the timescale of the dynamics is used in experiments on ultracold atoms trapped in optical lattices to imprint complex phases on the hopping amplitudes, and thus simulate topological insulators[21]. The effects of a drive with a timescale longer than that of the dynamics is more difficult to describe, and it is in this limit that topologically protected edge states can arise even if the topological invariants of the quasienergy bands of the effective Hamiltonian are all trivial[22]. The simplest toy models that display such novel topological phases are quantum walks[23,24].

Although the theory of topological insulators relies on quantum physics, many of the concepts carry over to classical mechanics. Specially engineered systems of springs and sticks can contain topologically protected modes on the edges[25] or at defects[26], and concepts of topological insulators have been invoked to explain the origin of equatorial waves in the ocean and the atmosphere[27].

In the last thirty-odd years, topological insulators have had a lasting impact on condensed matter physics. They have offered us a glimpse into the rich world of phase transitions that are not driven by a change in symmetry, but rather in topology. Moreover, the defining physical processes in topological insulators are “superficial”; they take place on the boundary of a material. Nevertheless, they are connected to the topological nature of the depths of the material, of the bulk. Thus, in topological insulators, the deep controls the superficial. ■

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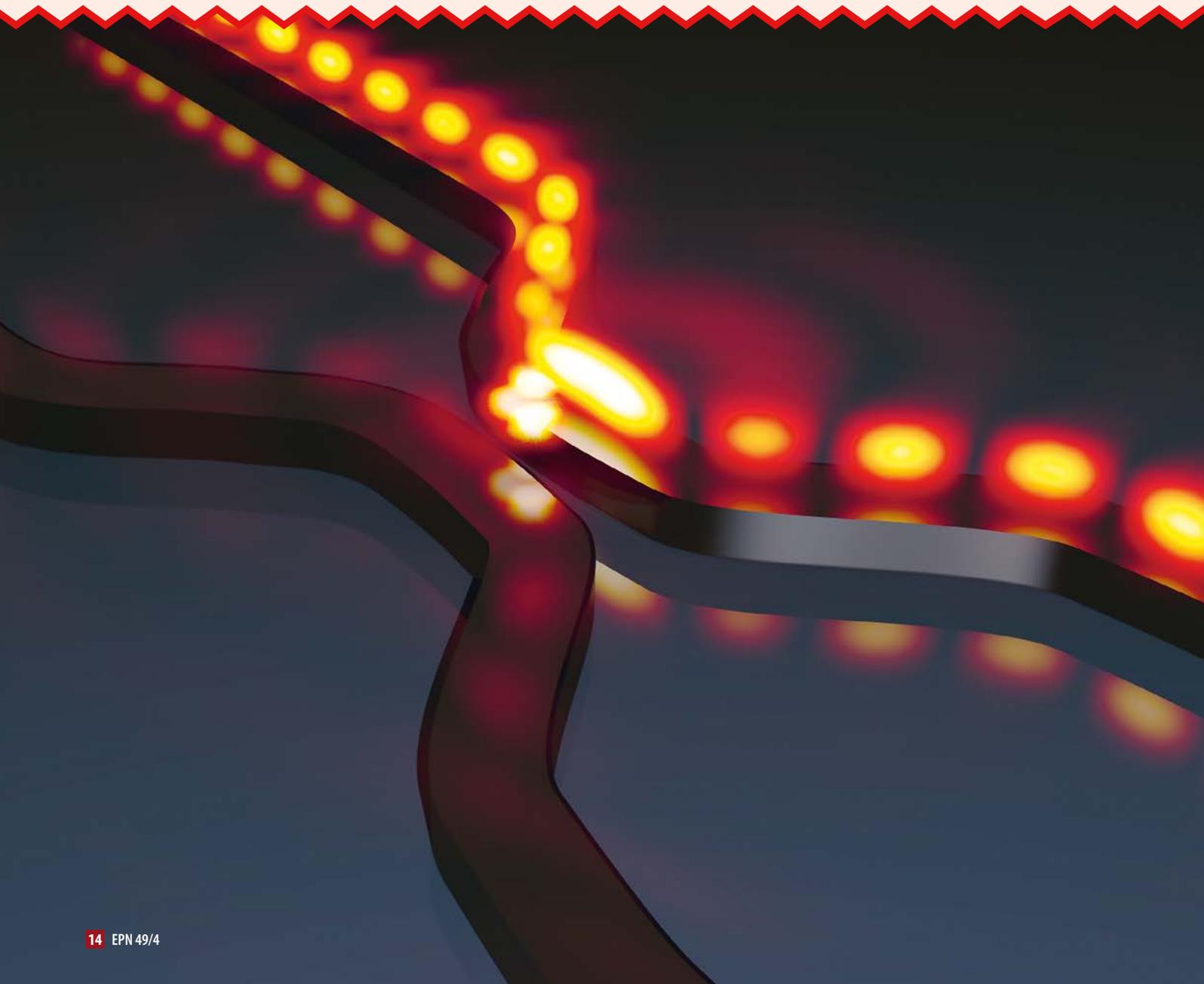


# NOT EVERY DIPOLE IS THE SAME: THE HIDDEN PATTERNS OF DIPOLAR NEAR FIELDS

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Nanophotonics is a fast-evolving scientific field studying light at the nanoscale. Its fascinating advances typically stem from concepts in modern physics, such as quantum optics, photonic crystals and optomechanics [1]. Occasionally, new insights appear even from the classical Maxwell’s equations of electromagnetism themselves [2].



Here we outline recently uncovered features of dipoles, the humblest among electromagnetic sources, whose interactions with a nearby structure can nevertheless be unexpectedly rich in terms of their selective excitation of guided modes. This has important applications throughout nanophotonics, from optical information technologies to the design of advanced photonic devices.

Dipolar sources are ubiquitous in every branch of nanophotonics due to their universality. Atoms, quantum dots and other point-like sources, when emitting light, behave as dipoles. Light scattered off any small illuminated particle also does. Matter itself, in its interaction with light, can be regarded as a collection of point dipoles. Dipoles are technologically important; in nanophotonics they are a fundamental tool for the analysis and design of experiments involving near-field instrumentation such as the detector tips in near field optical microscopy or the optical excitations caused by incident electron beams in a cathodoluminescence scanning electron microscope. These kinds of equipment rely on their interaction with optical near-fields of structures – for which the dipole model is perfectly suited. In fact, it is in the properties of these near-field interactions that new behaviours have recently been observed.

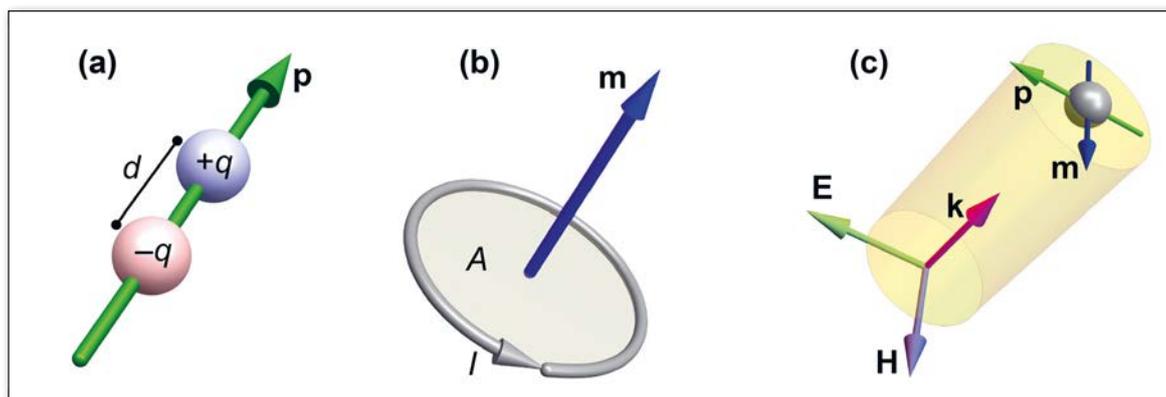
### Fundamentals of dipolar sources

Unlike classical gravitational fields, which can be well approximated to first order with knowledge of the total mass of objects, electromagnetic fields may originate from sources with a net zero charge, and so one looks at the next dominant term in the series expansion: the dipole. As we all know, electromagnetic dipoles come in two varieties: electric and magnetic (Fig 1). Electric and magnetic dipole moments  $\mathbf{p}(t)$  and  $\mathbf{m}(t)$  vary with time. Fortunately, the superposition principle allows us to consider the monochromatic constituents of any time dependent dipole, such that we may study a harmonically oscillating dipolar source radiating fields of a given, fixed, wavelength. This allows us to eliminate the time-dependence in the dipole moments, at the expense of using complex vectors  $\mathbf{p}$  and  $\mathbf{m}$  with real and

imaginary components accounting for the amplitude and phase of their sinusoidal oscillation. For example,  $\mathbf{p}=(1,1,0)$  corresponds to a linearly polarized dipole, oscillating parallel to the  $x=y$  line, while  $\mathbf{p}=(1,i,0)$  corresponds to a circularly polarized electric dipole, rotating anticlockwise in the  $xy$  plane. The complex nature of the dipole moment, which fully determines its phase, amplitude and polarization, is at the heart of the dipole's remarkable directionality properties. The experimental realization in optical laboratories of electric and magnetic dipoles with determined polarizations is simple. One way is via illumination of small particles which become electrically and magnetically polarized (Fig. 1c). The polarization of the dipolar source that can be generated with this method depends on two factors, the first being the polarization of the fields incident on the particle, which can be easily manipulated. The second factor is the polarizability response of the nanoparticle, which varies in amplitude and phase depending on particle geometry and working wavelength. A fine control on these elements can ensure the possibility to generate any desired dipolar source with an arbitrary polarization.

### Directionality of circularly polarized dipoles

A first hint that not all dipoles are equal came from the stunning, elegant behaviour of circularly polarized dipoles. We always resort to linearly polarized dipoles when we learn, think, and teach about them, with the assumption that any other polarized dipole is just a superposition of linear ones: while true, this neglects the fact that superposition and interference can yield interesting physical effects. Interference is usually associated with the propagation phase acquired by light along different trajectories, but it also applies to the near fields. Fig. 2(a) depicts a linearly polarized dipole  $\mathbf{p}=(1,1,0)$  radiating in free space, with its familiar radiation diagram. Fig. 2(b) shows this same dipole placed close to an optical waveguide – and we see that optical modes are excited. This is possible thanks to the dipole near-fields. The coupling interaction between point dipoles



◀ **FIG. 1:** (a) The electric dipole moment vector  $\mathbf{p}$  is the product between the charge constituting each of its poles  $q$ , and their separation distance  $d$ . (b) The magnetic dipole moment vector  $\mathbf{m}$  is the product between the amplitude of a circulating current  $I$  and the area it encloses  $A\hat{n}$ , in a direction  $\hat{n}$  normal to the area. Both converge to point sources in the appropriate limit. (c) A polarizable particle being illuminated by an incident beam with wave-vector  $\mathbf{k}$ , electric field  $\mathbf{E}$ , and magnetic field  $\mathbf{H}$ . The particle becomes polarized and behaves like a dipolar source with dipole moments proportional to the incident fields  $\mathbf{p}=\alpha_e\mathbf{E}$  and  $\mathbf{m}=\alpha_m\mathbf{H}$  with  $\alpha_{e/m}$  representing complex proportionality constants, which are the particle's electric and magnetic polarizability.

## BOX 1. A VARIETY OF EXPLANATIONS FOR THE NEAR-FIELD DIRECTIONALITY OF DIPOLES CAN BE GIVEN, ALL BEING ULTIMATELY EQUIVALENT, BUT EACH HIGHLIGHTING DIFFERENT ASPECTS.

- **Phase matching between the dipole fields and the waveguide:**

the phase matching of fields along smooth interfaces requires that the moving wave-fronts of a source must match the moving wave-fronts of the mode being excited. Consider the fields radiated from the circular dipole depicted in Fig. 2(c). Its wave-fronts are counter-clockwise rotating spirals. Clearly, if a waveguide is placed below the dipole as in Fig. 2(d), the wave-fronts sweep the waveguide from left to right, matching the wave-fronts of the guided mode propagating in the waveguide in the left to right direction, which gets excited. Indeed, placing the waveguide above the dipole would switch the directionality to the left, in agreement with a water-wheel analogy.

- **Superposition of excitations with different symmetries:**

consider a vertically polarized dipole  $\mathbf{p} = a\hat{\mathbf{y}}$ , over a dielectric waveguide. Due to the complete mirror symmetry of the problem, modes are excited in the waveguide in both directions, exactly in phase. The field will have an even symmetry with respect to the mirror-symmetry plane. Now consider a horizontal dipole  $\mathbf{p} = b\hat{\mathbf{x}}$ . This dipole is oscillating, alternatively pointing left and right, and this will evidently excite modes in both directions with identical amplitude, but exactly out of phase, constituting an odd symmetry of excitation. By a judicious superposition of both, horizontal and vertical components of the dipole result in the addition of an even and an odd function, which may produce a highly asymmetrical total field resulting in unidirectional excitation. This is the case for the circular dipole. In general, any dipole  $\mathbf{p}$  and  $\mathbf{m}$  is a superposition of six

components, which can all interfere between each other.

- **Overlap of the dipole's fields with the guided fields:**

the amount of coupling between a dipolar source  $\mathbf{p}$  and  $\mathbf{m}$ , and a waveguided mode with electric and magnetic fields  $\mathbf{E}$  and  $\mathbf{B}$  (evaluated at the location of the dipole) is given by Fermi's golden rule  $|\mathbf{p}^* \cdot \mathbf{E} + \mathbf{m}^* \cdot \mathbf{B}|^2$  involving dot products between dipole moments and fields, where  $*$  signifies complex conjugation [11]. In the case of the circularly polarized electric dipole, the excitation along one direction is zero because  $\mathbf{p}^* \cdot \mathbf{E} = 0$  for the field of the mode in that direction. For example,  $(1, i, 0)^* \cdot (1, -i, 0) = 0$ . This happens because the electric field of the waveguided mode indeed has a near circular polarization  $\approx (1, \pm i, 0)$  whose handedness depends on its propagation direction, a phenomenon named spin-momentum locking [12], [13]. In a more general case, the expression  $\mathbf{p}^* \cdot \mathbf{E} + \mathbf{m}^* \cdot \mathbf{B}$  is composed of the sum of six different terms, corresponding to how each component of the dipole excites each mode: this sum may easily interfere destructively for certain dipoles and waveguide modes [14]. This explanation gives an equal focus to both the dipoles and the fields of the specific waveguide, betraying the fact that the directionality is a universal property of the dipole, valid for any waveguide. It has the advantage of being an exact valid explanation in any scenario, such as dipolar sources inside photonic crystals.

- **Angular spectrum of the dipolar fields:**

This explanation mathematically fleshes-out the

simple phase matching argument given above. It is most powerful when the dipole is placed near smooth interfaces which conserve momentum and thus allow us to apply phase matching arguments. With it, we realize that the directionality of the dipole is a property of the dipole itself, universal for any waveguide [15]. It is based on a careful analysis of the fields produced by a dipole [16], whose exact analytical form has been known for as long as Maxwell's equations themselves. The amplitude and phase of the electric field  $\mathbf{E}(\mathbf{r})$  originating from a dipole, at any point in space  $\mathbf{r}$ , can be written in a short single-line equation. We may then analyse this field by means of its spatial Fourier transform  $\mathbf{E}(\mathbf{r}) = \iiint d\mathbf{k} \mathbf{E}(\mathbf{k}) e^{i\mathbf{k} \cdot \mathbf{r}}$  where  $\mathbf{E}(\mathbf{k})$  is the constant electric field amplitude of a plane wave or evanescent wave with wave-vector  $\mathbf{k} = (k_x, k_y, k_z)$  and  $e^{i\mathbf{k} \cdot \mathbf{r}}$  describes its propagation or attenuation through space. We have "spread out" the field into its spatial components, called its spatial or angular spectrum. In the phase matching argument above, we pointed out from an intuitive and hand-wavy argument that the phase fronts of a circularly polarized dipole sweep from left to right when looking below the dipole, explaining its directionality. Indeed, the angular spectrum of such dipole reveals the dominance of evanescent components with wave-vectors  $\mathbf{k}$  pointing from left to right when looking from below the dipole [15], providing a solid quantitative foundation to our intuitive notion. Janus and Huygens dipoles exhibit similar imbalances in their angular spectra, fully explaining their behaviour and symmetries.

and nearby waveguides is a well-known property of dipolar sources. Fig. 2(c) shows a circularly polarized dipole  $\mathbf{p}=(1,i,0)$  radiating in free space, and Fig. 2(d) shows the same dipole near an optical waveguide [3]. We see that, surprisingly and despite the mirror symmetry of this structure, the circularly polarized dipole excites modes in a single direction of the waveguide. This is a fundamental behaviour of the dipole, inherently broadband, robust to losses and imperfections. Remarkably, it admits many different but equivalent explanations, detailed in Box 1. The excitation of light modes from this circularly polarized dipole resembles a water wheel for light. When a circularly polarized dipole is sandwiched between two waveguides (Fig 3a), both are excited in opposite directions. Known for a few years now, this unique directionality has yielded fascinating applications such as ultracompact broadband optical nanorouting [3], [4], polarization analysers [5], quantum optical applications [6] including non-reciprocal nanophotonic devices [7], exotic lateral optical and Casimir forces [8], [9], generation of polarized light [10], and many others. And yet this dipole is but a first taste of how not every dipole is the same.

### Beyond circularly polarized dipoles: a zoo of directional dipoles

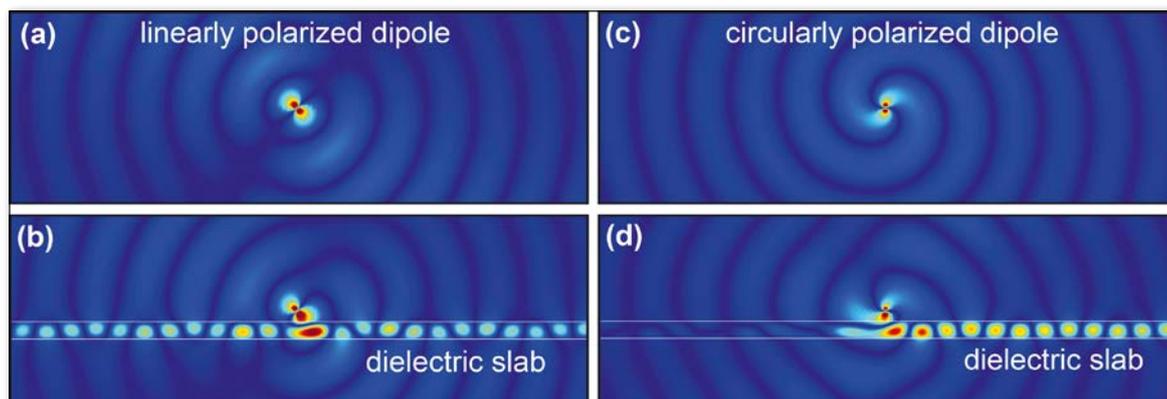
Using the analysis techniques described in Box 1, we recently asked ourselves what other unconventional dipolar sources could be found. By combining electric and magnetic dipoles together, new directional dipolar source behaviours are revealed [14]. The idea of combining electric and magnetic dipoles to obtain distinct functionality is not new. The Huygens dipole is a source which combines two linearly polarized orthogonal electric  $\mathbf{p}$  and magnetic  $\mathbf{m}$  dipoles with an amplitude ratio of  $p=m/c$ , where  $c$  is the speed of light, such that their combined radiation is directional in the far-field in the  $\mathbf{p}\times\mathbf{m}$  direction. For example,  $\mathbf{p}=(1,0,0)$  and  $\mathbf{m}=(0,c,0)$  show complete far field directionality in the  $+z$  direction. The radiation of the electric and magnetic dipoles, omnidirectional when on their own, interfere destructively in one direction but constructively in the opposite

one, resulting in unidirectionality. This has been used to create engineered surfaces with perfect reflection, and all-dielectric mirrors among other applications [17]. It turns out that the same phenomenon exists in the dipole's near-field [14]. The Huygens dipole exhibits a different symmetry of near-field excitation compared to the circular one: when sandwiched between waveguides, it couples to the modes in the waveguides along the same direction for both (Fig. 3b).

Both circular and Huygens' dipole appear as solutions of a single equation, yet a third solution completes the set [14]. This novel dipole greatly resembles the Huygens' dipole, in that it too is a combination of linearly polarized and orthogonal dipoles, but its electric and magnetic dipoles are in quadrature phase, that is, with a  $\pi/2$  phase difference between dipole moment amplitudes. It does not show any directional behaviour in the far-field, and yet it shows unique and surprising properties in its near field coupling. This source, like its namesake ancient Roman god Janus, has two faces. One face enables coupling into nearby waveguides, while the opposite face is non-coupling to them. Therefore, flipping the Janus dipole's face as if it were a coin, enables switching the coupling on or off. Equivalently, the binary state of the coupling depends on which side of the dipole the waveguide is placed. When sandwiched between two waveguides, the Janus dipole couples to both directions on the same waveguide, the one facing its coupling side, while blatantly ignoring the other one (Fig. 3c). These new near-field dipolar sources all follow the same explanations given in Box 1, ultimately relying on near-field interference between distinct dipolar components.

### Conclusions

The three elemental dipoles shown in Fig. 3 arise as solutions from one same equation, describing dipole directionality in a simplified planar waveguide scenario [14]. In fact, any linear combination of the three elemental sources results in an infinite range of possible directional dipole sources. More complex three-dimensional scenarios and more complex waveguide geometries will enable even further examples of directional



◀ FIG. 2: Snapshot of radiated magnetic field amplitude of a linearly (a,b) and circularly (c,d) polarized electric dipole radiating either in free-space (a,c) or at a subwavelength distance  $0.1\lambda$  near a dielectric waveguide (b,d). The phenomenon exists for any kind of waveguide. In this figure we chose a dielectric slab with refractive index  $n=3$  and thickness  $t=0.2\lambda$ .

► **FIG. 3:** Behaviour of three different dipolar sources: (a) circular (b) Huygens and (c) Janus dipoles, sandwiched between two standard silicon nanophotonic waveguides. The dipole moments were optimized for optimal directionality contrast as described in Ref. [14]. The figure renders a snapshot of the field intensity of a real three dimensional numerical simulation. The simulation was performed in the commercial electromagnetic solver CST Microwave Studio. The fields are shown shifted in space so that they appear above the waveguides instead of inside. The cross section of these silicon waveguides is  $(0.2 \times 0.16)\lambda$ . The refractive index of silicon at  $\lambda=1550$  nm was taken as  $n = 3.45$ . Notice that the three sources are intimately related to the three spatial symmetries of the underlying structure: two mirror symmetries along orthogonal planes, and a half-turn rotational symmetry.

dipoles, opening a zoo of possibilities. The behaviour is fundamental and robust. Given the amount of applications that arose from circularly polarized dipoles alone, we expect these new dipolar possibilities to give rise to a plethora of new ideas. As a simple example, the directionality of circularly polarized dipoles was used as a method for local measurement of the transverse electric field polarization: the generalization of the concept will allow local measurement of all spatial components of both electric and magnetic fields in complex structured electromagnetic beams. New ideas can arise in a wide array of areas such as quantum optics, optical logical circuits, photonic nanorouting, polarization detection and synthesis, novel optical forces and torques in nanoparticles, and hopefully in as yet unforeseen devices throughout nanophotonics and other regions of the electromagnetic spectrum. ■

### Acknowledgements

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### About the authors



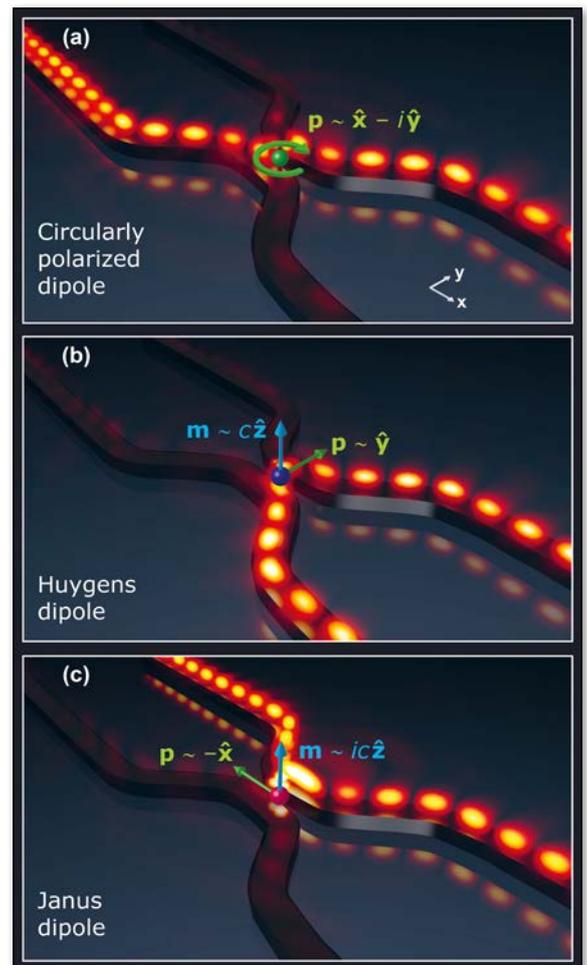
**Michela F. Picardi** is a PhD student at King's College London, UK, under the supervision of Francisco J. Rodríguez-Fortuño. Her project is devoted to the exploration of degrees of freedom of light and their mutual interactions, as well as their behaviour in nanophotonic and plasmonic environments for future light-based technologies.



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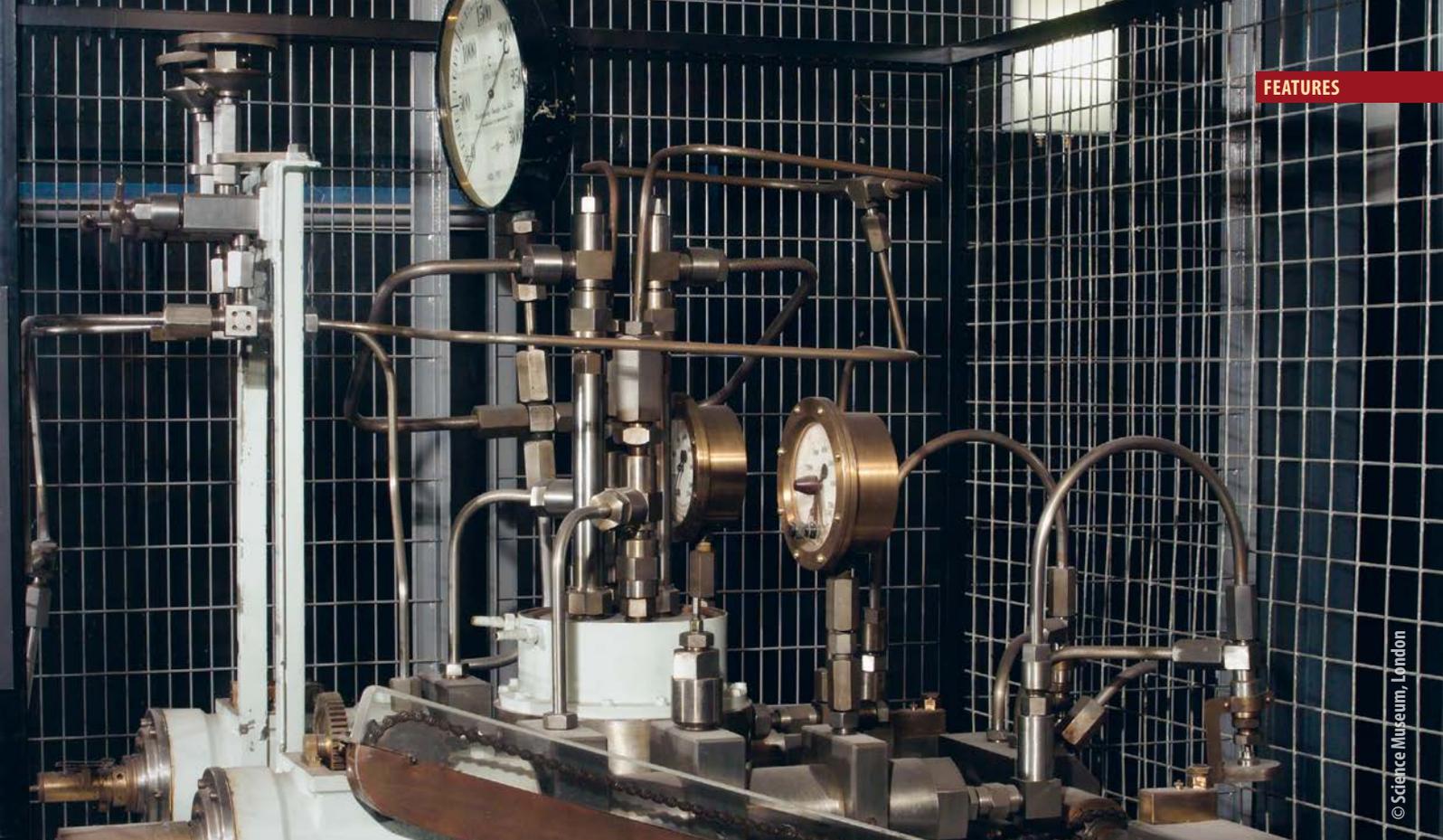


**Francisco J. Rodríguez-Fortuño** is a Lecturer at the Department of Physics, King's College London. His research focuses on plasmonic devices, optical forces, optical nanoantennas, metamaterials and novel electromagnetic phenomena. Francisco is a member of the editorial board of Scientific Reports and is a principal investigator on the European Research Council Starting Grant 714151 PSINFONI.



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# HOW POLYETHENE CAME ABOUT

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**Polyethene (PE) is the world's most common polymer, with applications from low-cost to extreme-performance products. Its origin, as low-density LDPE, can be traced back to a long tradition in fundamental thermodynamics and to a liberal international university-industry collaboration. A first application became of world-wide significance 75 years ago.**

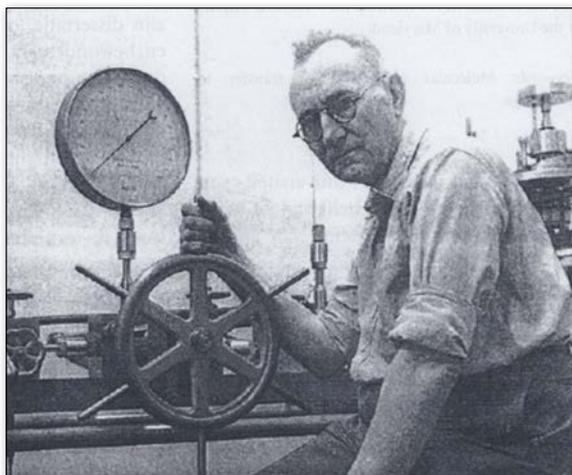
**W**hen Van der Waals received his Nobel Prize in 1910, two years after his retirement, the field of fluid thermodynamics that he had initiated was flourishing already for more than thirty years. His successor in Amsterdam Philipp Kohnstamm and other prominent researchers had expanded it into a strong Dutch scientific tradition [1]. The existence of molecules and their universal interaction was a daring assumption by Van der Waals in 1873 against much opposition at that time, but with scientific progress in the early 20<sup>th</sup> century his views became universally accepted. In spite of this progress, a more detailed picture of the molecular properties and of the origin of the intermolecular interaction remained elusive. As a consequence the field became stagnant around 1915-1920. Kohnstamm's interests shifted to pedagogy

and philosophy. Students preferred the new quantum theory, particularly in Amsterdam, where Nobelist Pieter Zeeman broke new ground in atomic spectra.

## High-pressure physics

One of the few students who continued in the Van der Waals tradition was A.M.J.F. Michels (Fig. 1), my father, who had entered the university in 1909. He recognised that quantum theory promised insight also in molecules, which could open new avenues for the understanding of compressed gases and liquids. Conversely, by compressing gases to levels where molecules get in close contact, thermodynamic and electromagnetic studies could become informative about molecular details that should obey quantum theory. He figured that this would require pressures up to a few thousand atmospheres. In 1929, as a successor to

► FIG. 1: Antonius (Teun) Michels, with his oil press for generating high pressures [Source: Michels family archive]



Kohnstamm, he presented all this as the agenda for a future specialised high-precision high-pressure laboratory. But back in 1920 there were significant technical hurdles to take first before such academic questions could be addressed. The accuracy in methods of measuring temperature and especially pressure were far below what was needed, and he spent a decade and longer on developing improvements. His most conspicuous achievement was the design in 1924 of what is now known as the 'Michels pressure balance'; with its frictionless rotating piston it instantly improved the accuracy in pressure measurement up to 3000 atm. by more than a factor 100, to 1:100,000. For calibration a 27.5 m mercury column was erected in Amsterdam's tallest church spire, the 'Westertoren'. This and other technical high-pressure work was a long and necessary preparation for his real agenda, but at the university it earned him an unwanted reputation of being more technically than scientifically motivated. He used it to his advantage when by chance he came in contact with industry.

## ICI

Michels had very limited university funding. But still a bachelor, with a strong motivation and much energy, he had side-jobs as a high-school teacher and worked in the laboratory at evening and night hours, spending personal earnings on equipment and assistance. In this situation he was visited in 1925 by Reginald Gibson (Fig. 2), a young chemist from London who was temporarily hired by Kamerlingh Onnes in Leiden and would join the British Imperial Chemical Industries a year later; Gibson was facing a technical problem on which he thought Michels could help. Gibson was immediately interested in the pioneering work in Amsterdam and offered to assist part-time. After joining ICI, Gibson invited Michels for a Christmas stay in England, where he also introduced him to ICI management - with far-reaching consequences on both sides. When a delegation of ICI visited the Amsterdam laboratory in 1928, they recognised the enormous potential of the new high-pressure techniques for their own goals, their thoughts being mainly on phase behaviour

► FIG. 2: Reginald Gibson in his Amsterdam period [Source: Michels family archive]

and material characterisation; no ideas occurred on links to chemistry. In their visit report they did conclude that "if there were an army of research workers co-operating with Amsterdam [...], results of industrial application would undoubtedly be obtained too quickly to be assimilated". The outcome was that ICI agreed to support Michels with substantial means, on the condition that he would stop his side-job teaching and that ICI staff would be trained in Amsterdam in the high-pressure techniques. As a result Kohnstamm stepped aside and Michels became reader in thermodynamics. Gibson was the first ICI employee to work in Amsterdam, where he also obtained his PhD. His arrival was soon followed in 1929 by that of Michael Perrin (Fig. 3), who had already degrees from Oxford and Toronto and who stayed in Amsterdam till 1933 [2].

## From physics to chemistry

Publications, notably by Bridgman and Conant at Harvard, reported that polymerisation reactions may be affected by very high pressures; but measurements remained crude and results unclear. First theoretical thoughts about possible novel effects of pressures on reactivity appeared on paper in 1930, after Michels participated in a Royal Society Discussion Meeting on high-pressure chemistry. The account of this meeting [3] starts with contributions by British specialists, discussing chemical processes up to a few hundred atm.; here the main pressure effects are the classical ones of shifting reaction equilibria or changing solvency. Apparently not without self-confidence in this illustrious gathering, Michels starts his contribution by stating that "in Amsterdam [...] we refer to pressures up to 2500 atm. as low, pressures between 2500 and 10,000 atm. are regarded as medium, and pressures above 10,000 atm. are regarded as high". Then he points out how in compressing gases potential energy is stored which may ultimately be sufficient to distort molecules and trigger chemical reactions that normally will not occur (see Box). In personal notes from the same time Michels (who also had a degree in chemistry) showed a particular interest in



organic reactions. He is then invited in 1931 to present his ideas to the research committee of the ICI Dyestuff Group, under the title “Suggestions as to the influence of high pressure upon chemical reactions”. No written version of the presentation seems to have survived, but in 1932 Perrin (still in Amsterdam) and John Swallow (at ICI) discuss its theoretical arguments in a proposal to the ICI Alkali Division for a research programme on chemistry between 1000 and 20,000 atm., aiming to connect these arguments with Bridgman’s type of experiments. The 1931 presentation by Michels aroused direct interest and at the request of ICI one external member of the committee, professor Robert Robinson, listed a number of candidate reactions; Gibson and Eric Fawcett were asked to make a start with it.

## Polyethene

One of the attempts was to react ethene and benzaldehyde into a lubricant. On Friday March 24, 1933 Fawcett and Gibson filled the reactor and left it at 170 C and 1900 atm. (Fig. 4). When they returned on Monday a leak had developed and the pressure had gone. Opening the reactor they discovered a “waxy solid in reaction tube”, as it was recorded in Gibson’s notebook. After some study it was realised that ethene had polymerised. But when the reaction was repeated with ethene alone it frequently ended in an explosive decomposition, producing just hydrogen, methane and amorphous carbon. A ban was ordered on working with ethene, the early results were left as an academic curiosity and the focus shifted to other reactions. In December 1935 Perrin, after discussion with ICI’s engineer Dermot Manning, revisited the problem in a ‘clandestine’ experiment, as Manning told later. They benefitted from experience now gained with other reactions and from improved equipment, but for safety operated after normal working hours. Not surprised, Perrin saw the pressure slowly drop and supposed that ethene was reacting away; continuously readjusting the pressure by feeding in fresh ethene, he got the polymerisation under control and a test tube filled with white powder was obtained. Afterwards it was discovered that the pressure drop had been partly due to a leak again. On December 20 the first official controlled ethene polymerisation was recorded by Perrin, John Paton and Edmond Williams. But in later attempts explosions returned. It took months of analysis to recognise that oxygen impurities in the ethene are essential to initiate the reaction at the chosen pressures (see Box); in the first try the impurity in the continued feed just happened to be high enough for sustained reaction but low enough to avoid explosion. The new polymer was now taken seriously and it soon turned out that it could be very easily processed and shaped, was chemically resistant and water-repellent, did not embrittle at very low temperatures or melt in boiling water, and had exceptional properties as an electric insulator. In 1938 a pilot plant, with an unconventional continuous gas compressor that had to be designed in



◀ FIG. 3: Michael Perrin (left), with Michels’ theoretician Arend Rutgers (a student of Ehrenfest and later professor of Physical Chemistry in Ghent) in the wooden annex to the old laboratory. Perrin also played a leading role in British and Allied nuclear research during and after WW II; he was knighted in 1967 [Source: Michels family archive]

Amsterdam [4] (see introductory illustration), produced the first tonnes of polyethene. Application as insulation of subsea communication cables was envisaged.

## Airborne radar and the U-boat war

World War II changed it all. Radar had already been developed, but its installation in planes called for shorter wavelengths (using the recently invented cavity magnetron) and faced the very cold and humid conditions high in the air. With the weak reflection signal, cable insulation proved to be the critical problem; but the moisture-repellent polymer, with its excellent mechanical and exceptional high-frequency dielectric properties, could solve it. Robert Watson-Watt, the pioneer of British radar (and a descendant of James Watt), later declared that polyethene transformed the construction of airborne radar “*from the almost insoluble to the comfortably manageable*” [4]; it had some success already at the end of the Blitz on London. But early 1943 the Nazi-German U-boat campaign threatened to starve Britain from the essential supplies needed for its survival and for the future liberation of Europe. Churchill has confessed in his memoirs that the



◀ FIG. 4: Apparatus used by Fawcett and Gibson in the discovery of polyethene in 1933. Next to the ethene feed are a primary gas compressor, the reactor vessel (filled with oil, a mercury interphase, and liquid benzaldehyde) and the oil press for reaching up to 3000 atm. [© Science Museum, London]

only thing that ever really frightened him during the war was the U-boat peril [5]. In the spring of that year, 75 years ago, the centrimetric radar with polyethene insulation came in operation. Within a month the tide turned completely and U-boat losses suddenly rose to huge numbers. Admiral Dönitz realised that his campaign had failed and that “*the U-boats could be located at a great distance by the enemy’s radar, apparently on short wave, without previous warning on their own receivers. [...] The enemy air force with its modern methods of searching had produced this change in U-boat warfare*” [6]. The critical role of polyethene and how it originated were recalled directly after the war by an ICI manager in a letter to Michels: “*There has been public acknowledgement of the value of our products in the war effort and I am glad to think that some share of it is due to you*” [7].

### Epilogue

The liberal industry-university collaboration proved beneficial also in other ways to the parties involved. Although ICI recently has ceased to exist as an independent company, its high-pressure process is still operated today by many manufacturers of LDPE. Michels obtained a professorial chair in 1939 and the industrial support was instrumental to open a splendid new ‘Van der Waals laboratory’ already

in 1935; after the war it became world-leading in the molecular study of gases and liquids by high pressure. When in the 1950’s Michels could not be persuaded to emigrate to the USA, he was asked to build a copy of his laboratory at the University of Maryland: the ‘Institute of Molecular Physics’ [8]. ICI equipment in which polyethene was synthesised and the continuous gas compressor from the Van der Waals laboratory are now at the Science Museum in London. Looking back in 1980, Reginald Gibson concluded with the philosophy of the industry’s founder Ludwig Mond: referring to the common notion that ‘necessity is the mother of invention’, Mond rather trusted that “*the steady methodical investigation of natural phenomena is the father of industrial progress*” [2]. A philosophy that was fittingly written on the commemoration plaque in the ICI Winton laboratory where polyethene was discovered. ■

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Thanks are due to dr. Jacques Joosten (DPI) and prof. Jan Sengers (Maryland) for stimulation and advice.

### About the author



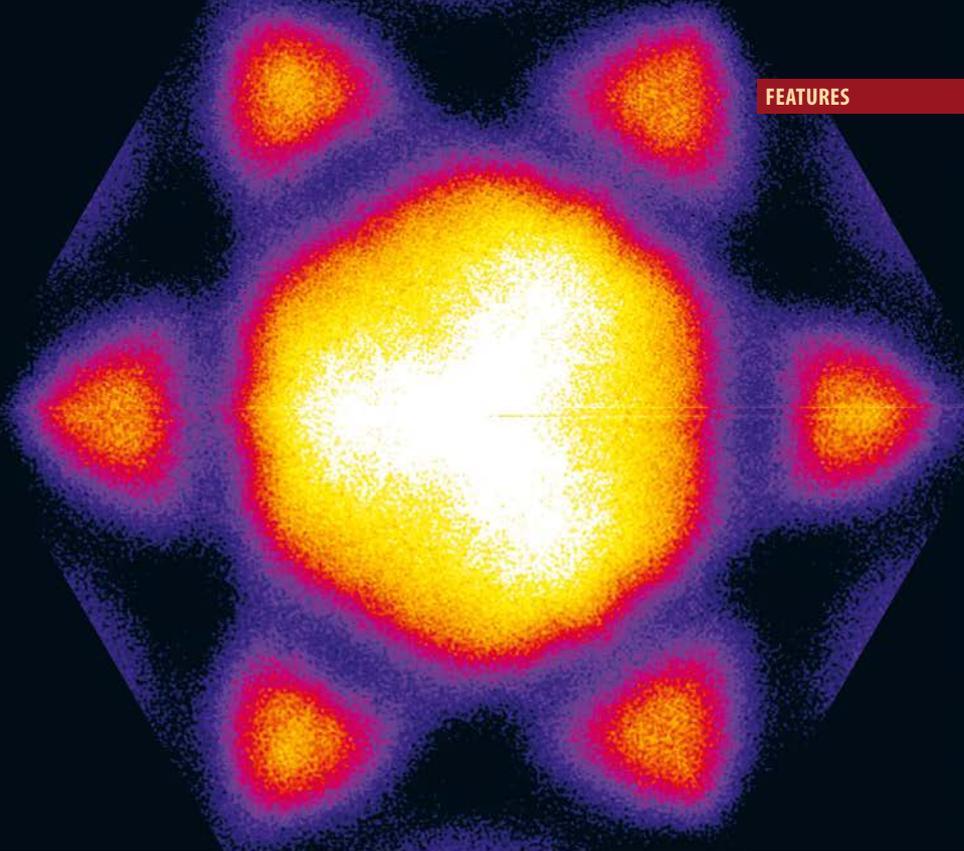
**M.A.J. (Thijs) Michels** is emeritus professor of Theoretical and Polymer Physics at the Eindhoven University of Technology and a former Scientific Director of the Dutch Polymer Institute (DPI), an international public-private partnership in polymer research. He has also worked 20 years in research of oil processes and products at the Shell laboratory, Amsterdam.

### BOX: THE INTERMOLECULAR AND INTRAMOLECULAR ENERGIES OF ISOTHERMALLY COMPRESSED GASES

*Equation of state and internal energy.* The thermodynamic relation  $(\partial U/\partial V)_T = -p + T(\partial p/\partial T)_V$ , tells that internal energy  $\Delta U$  due to molecular interaction increases with isothermal compression as soon as  $(\partial \log p/\partial \log T)_V < 1$ . By integration along accurately measured isotherms  $p(V, T)$  it was found in Amsterdam that at a few thousand atm.  $\Delta U$  might reach values comparable to chemical activation energies. *The Schottky relation and intramolecular energy.* Equations of state are often derived as power series in  $V$  by applying the well-known virial theorem to the interacting molecules, with virial coefficients that are complicated integrals over the interaction potential. The virial theorem can also be applied to the charged electrons and nuclei that constitute the same molecules and that interact via the simple Coulomb potential. This leads to the compact Schottky relation  $U = 3pV - K$ , with  $K$  the kinetic energy. At isothermal compression any change in  $K$  should be of intramolecular origin, *i.e.*, due to molecular deformation. For ethene  $\Delta K_{\text{intramol}}$  has been calculated from isotherms [9], giving about 7 kcal/mol at 170 C and 1900 atm. *The role of nuclei and the reaction initiation by oxygen.* A quantum-chemical treatment of the distortion of the ethene molecule was still out of order many years later, but in 1950 Cottrell could address simpler molecules [10]. He showed that much of the rise in  $K$  was compensated by a virial contribution of shifting nuclear positions, and that the rise in electronic energies was at least one order smaller than otherwise expected. This explains why traces of oxygen were also necessary as reaction initiator.

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# A NEW PERSPECTIVE ON NEW MATERIALS

■ Johannes Jobst & Sense Jan van der Molen – DOI: <https://doi.org/10.1051/eprn/2018404>

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**We live in an age of nanomaterials in which new materials are discovered almost every day. Moreover, we are starting to engineer material properties at the nanoscale. Hence, we need new tools to investigate different materials routinely and on small length scales.**

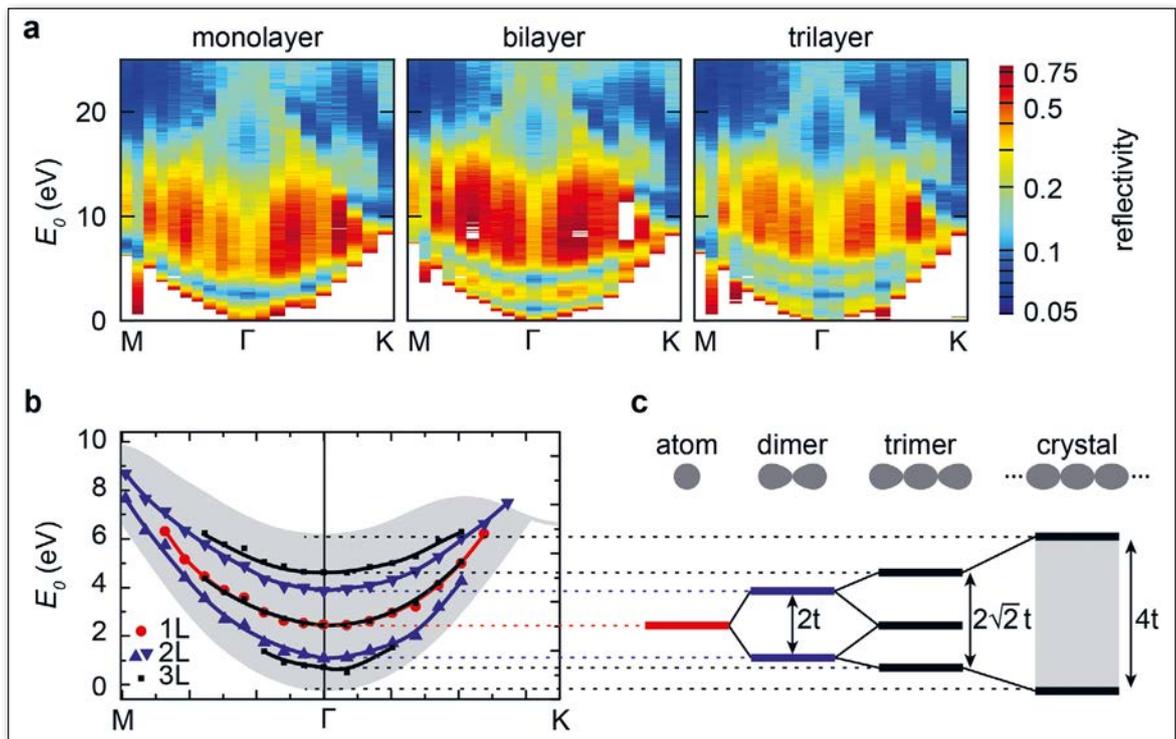
**T**he ages of human history are classified by the materials used for the most innovative technologies at that time. Although we made a great leap from the biface in the stone ages to computers and the internet in our digital, connected silicon age, it is still difficult to predict which material will define future societies. Consequently, many new materials are under investigation today for a wide range of applications of tomorrow. These materials are typically only available in small quantities or are relatively inhomogeneous on the sub-micron scale. This limits the use of many optical techniques as they lead to an averaged result at best. Instead, what one wants are tools that can find tiny areas of interest on a sample and take meaningful data from it. In the best case, even local variations can be resolved. Good lateral resolution is crucial for materials where the properties are intentionally tuned by local,

nanoscopic modifications. A particularly pronounced example of these are the so-called Van der Waals materials, artificial stacks of atomically thin sheets of layered crystals such as graphite (conductor), hexagonal boron nitride (insulator) or transition metal dichalcogenides (semiconductor). Isolated atomic planes can be reassembled into designer heterostructures made layer by layer in a precisely chosen sequence. The local assembly of these layers and their orientation with respect to each other strongly modify the properties of the whole stack [1].

## Measuring the Band Structure

One of the most important characteristics of a material is its band structure. It describes which momenta  $k$  and energies  $E$  are allowed for electrons within the material, which, in turn, determines most electronic and optical properties. The band structure is the analogy of atomic

► FIG. 1: ARRES measurements on monolayer, bilayer and trilayer graphene on SiC show quantized electron bands. Red/yellow corresponds to a band gap, blue to unoccupied states. (b) Quantized states extracted from (a) lie increasingly dense together as the graphene layer number increases. (c) This splitting in energy is caused by the interaction  $t$  between these states. This is analogous to the hybridization of atomic orbitals when chemical bonds are formed. Adapted from Ref. [3].



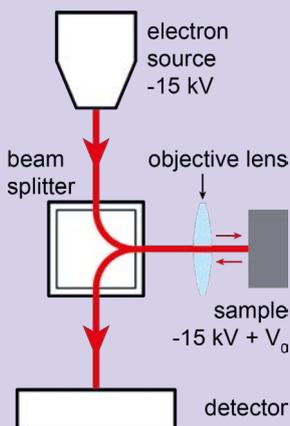
or molecular orbitals for crystals. Low-energy states are filled with electrons first while states at higher energy remain empty. This boundary between occupied and unoccupied electronic states is called the Fermi level. At

even higher energies, the attractive interaction between electrons and atomic cores becomes so weak that electrons in states above this so-called vacuum level will leave the material.

Band structures have been a topic of intense research for almost a century providing some of the most important insights in condensed matter physics [2]. In particular, angle-resolved photoemission spectroscopy (ARPES) has become one of the standard characterization tools for any newly discovered material. In ARPES electrons are emitted upon illumination with photons due to the photo-electric effect. Due to momentum and energy conservation in this process, the recorded energy and momentum of these electrons is a direct representation of the occupied states of a material. The photo excitation cross-section is small, however, and therefore either large samples or very bright, focused light sources (e.g. synchrotrons) are needed.

In addition, many samples are non-uniform even below the length scale that can be resolved in ARPES (~200 nm in state-of-the-art synchrotrons). This is particularly pronounced for Van der Waals materials. Consequently, we need another probe with higher interaction cross-section and shorter wavelength. Low-energy electron microscopy (LEEM, see Box 1) offers the perfect probe: **low-energy electrons have sub-nanometer wavelength** (above 2 eV) **and their reflectivity is determined by unoccupied bands** of the sample studied (see Box 2). Moreover, the energy  $E_0$  and in-plane wave vector  $k_{||}$  of the electrons used for imaging can be precisely chosen. Every pixel in the acquired images thus represent the local reflectivity

### BOX 1: LOW-ENERGY ELECTRON MICROSCOPY (LEEM)



In LEEM, surfaces are probed by a coherent beam of electrons whose landing energy  $E_0$  can be selected between 0 and 100 eV by decelerating them in a tunable electric field between objective lens and sample (see sketch).

The reflected electrons are re-accelerated into the objective lens, pass a magnetic beam splitter and are projected onto a detector to form an image [4-6]. Like in a normal light microscope, the full image is recorded at once with the local brightness given by the intensity  $I$  of electrons reflected from that area.

When LEEM images are recorded for different landing energies, every pixel in this image stack corresponds to a reflectivity spectrum  $I(E_0)$ . The reflection probability of low-energy electrons is intimately related to the band structure of the probed material [3,7,8]. In particular, electrons are transmitted into a material if states exist at their kinetic energy  $E_0$ , causing a minimum in the reflectivity spectrum  $I(E_0)$ . If no states are available (a band gap),  $I(E_0)$  has a maximum.

as a function of  $E_0$  and  $k_{||}$  and consequently also the local unoccupied band structure. We baptized this new method angle-resolved reflected-electron spectroscopy (ARRES) [3] by analogy with the name of ARPES. In fact, ARRES and ARPES are complimentary techniques as the former probes unoccupied bands above the vacuum level, whereas the latter measures occupied bands below the Fermi level.

### From Quantized States to Extended Bands

Due to this local character, we can use ARRES to study Van der Waals materials in the few-layer limit. **We can, thus, study how to build up a band structure from the bottom up, layer by layer.** Figure 1a shows ARRES measurements of the unoccupied band structure of monolayer, bilayer and trilayer graphene on silicon carbide. They all share a common region of high reflectivity (red area around  $E_0=10$  eV) that corresponds to a band gap. At lower energies, in contrast, the band structure of different layer number differs significantly. Monolayer graphene exhibits a pronounced band of unoccupied states (blue), while bilayer shows two and trilayer three of these bands. The single band in the monolayer system corresponds to a single interlayer state between the graphene layer and a carbon layer that terminates the SiC substrate (see Box 2). In bilayer graphene, a second interlayer state is present between the two graphene layers. Due to the close vicinity of the two states, they interact quantum mechanically. This leads to a splitting of the energy levels, analogous to

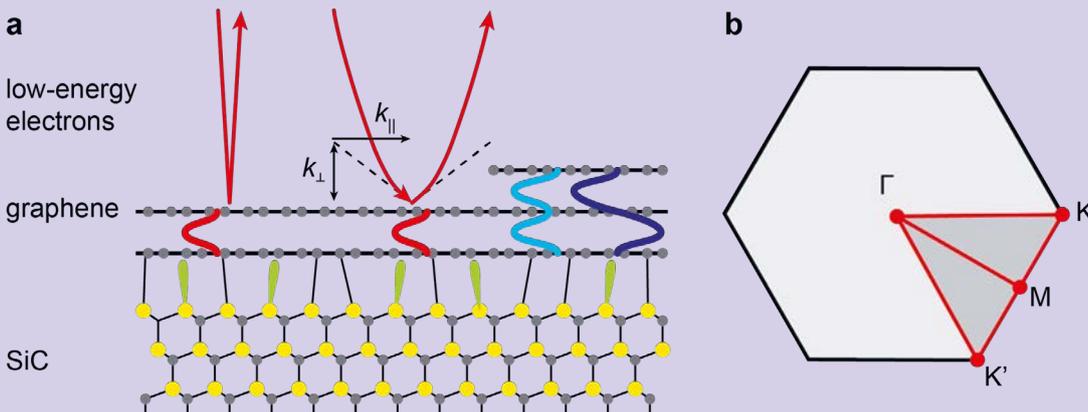
the tight-binding description of molecules: when the orbitals of two atoms overlap, they hybridize into a lower ‘binding’ and a higher-energy ‘anti-binding’ molecular orbital. In this analogy the individual interlayer states in graphene play the role of atomic orbitals. The important difference is that these ‘atomic’ states are quantized only in the out-of-plane direction, but quasi-infinite within the plane. They can thus be considered ‘two-dimensional atoms.’ Consequently, the splitting of the bands observed in ARRES (Fig. 1a) is a direct measure for the interaction strength of interlayer states in graphene.

Moreover, if we keep adding layers to the system, we can observe the evolution of individual quantum objects into the continuum of an extended crystal. Every additional layer contributes another interlayer state that interacts with the other states. This means that their spacing becomes smaller and smaller and eventually they all overlap to form a continuous electronic band (Fig. 1b). This case can be observed in graphite, which is an almost-infinite stack of graphene layers. Figure 2a shows the ARRES measurement of the unoccupied graphite bands (top panel) together with ARPES measurements of the occupied part (lower panel) acquired in the same instrument. Theoretical calculations (black lines) correspond very well with the measured data and, indeed, a continuous electronic band is observed between 0 and  $\sim 10$  eV (yellow in Fig. 2a).

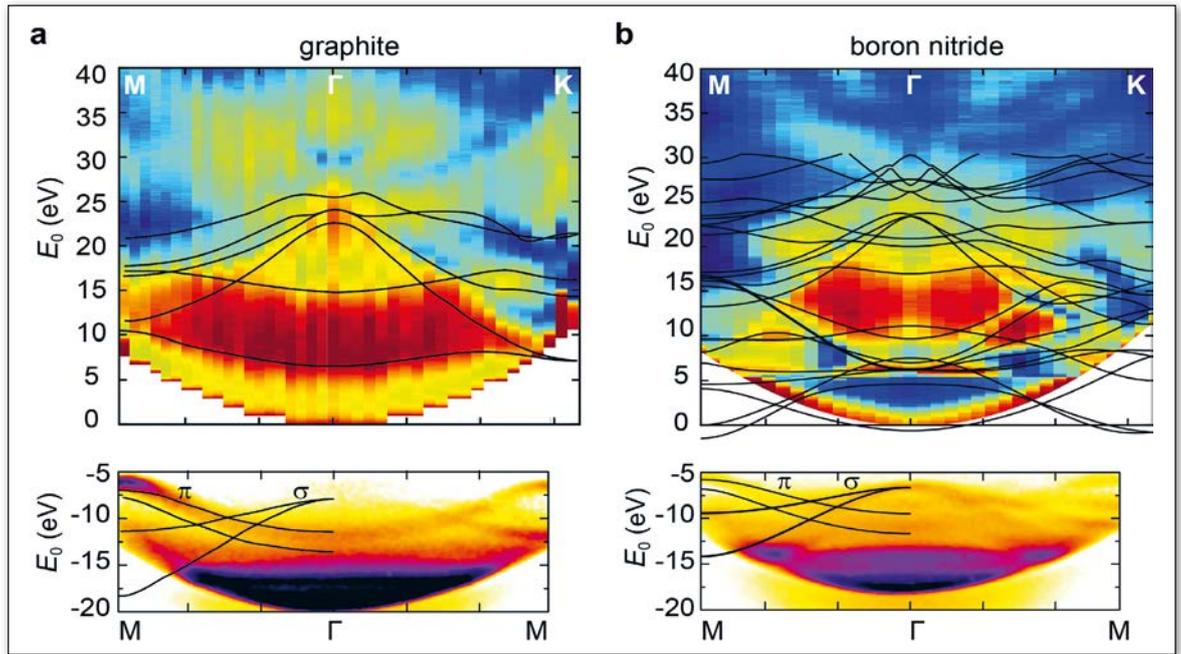
The wealth of information that is encoded in the unoccupied band structure of a material can be witnessed from the comparison of ARRES measurements on graphite and hexagonal boron nitride (hBN) in Fig. 2a and b. Although

#### BOX 2: SELECTING THE ELECTRON MOMENTUM

To measure any part of the band structure, the presence of electronic states has to be obtained as a function of electron energy  $E_0$  and in-plane momentum  $k_{||}$ . In LEEM, we can easily achieve this by tilting the incoming electron beam using electrostatic deflectors (like in an old TV based on cathode ray tubes) as sketched in (a). In fact, we can tilt the beam such that  $k_{||}$  follows the high-symmetry lines connecting the Gamma ( $\Gamma$ ), K and M points (b). They reflect the hexagonal symmetry of most Van der Waals materials and measuring the bands along those lines captures most of the physical properties. Normal incidence, *i.e.*,  $k_{||} = 0$  (left in a), corresponds to the Gamma point.



**► FIG. 2:**  
 ARRES (top) and  
 ARPES (bottom)  
 measurements show  
 the unoccupied  
 and occupied band  
 structure, respectively.  
 Pronounced  
 differences are visible  
 between graphite (a)  
 and hexagonal boron  
 nitride (b). The energy  
 offset between top  
 and bottom images  
 reflects the work  
 function, *i.e.*, the  
 energy difference  
 between Fermi level  
 and vacuum energy.  
 Black lines are  
 predictions by band  
 structure calculations.  
 Adapted from  
 Ref. [8].



they have the same crystal structure, their bands are vastly different<sup>1</sup> causing graphite to be a good electrical conductor while hBN is insulating. This shows how insightful band structure measurements are. The power of ARRES, however, goes well beyond fingerprinting different materials. Due to its high lateral resolution, **it opens a window to band structure effects on length scales not accessible to other methods.**

### Band Structure Engineering

This capability is crucial for the investigation of samples where the band structure is tailored by local modifications. In Van der Waals materials such band structure engineering can be achieved by the assembly of individual two-dimensional layers from different host crystals. This Lego-like approach renders it possible to construct materials from scratch that do not exist naturally. The large variety of available 2D crystals means that a sheer endless number of combinations are possible. Those Van der Waals materials can be further tailored by changing the stacking order of layers, the strain within layers or the rotation angle with which they are placed on top of one another [9, 10]. In addition, the layers and interfaces can be decorated with atoms or molecules. All those tuning parameters lead to local variations in the band structure that determine the final properties of the Van der Waals material. ARRES yields new insights into the band structure on those length scales [8]. A better fundamental understanding of this band structure engineering may allow us to design novel materials with desired properties for future technologies. ■

<sup>1</sup> The title image is a constant-energy cut through the hBN band structure at 12 eV obtained in ARRES.

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# A TRIBUTE TO MAX PLANCK

■ Henk Kubbinga – University of Groningen (The Netherlands) – DOI: <https://doi.org/10.1051/epn/2018405>

Physics seemed complete, in the 1890s. The accomplishments of the kinetic theory of gases were impressive, though some details remained to be solved. The new rays, of all kinds, were just novelties to be embedded in the well-established overall picture. Heat radiation, though, proved disturbing. In its purest form, emitted by a source at constant temperature and, subsequently, refracted by a prism, the spectrum being scanned by a bolometer, it produced curves similar to the statistical distributions current in the kinetic theory. Max Planck was the first to realize the far-reaching consequences. It brought him the Nobel Prize for Physics of 1918.

## The coming man; Munich, Kiel

Max Planck was born in 1858 in Kiel, a city on the northern coast of Germany, as the son of a professor of civil law at the local university. The family moved on to Munich, in 1867, where Planck junior attended a classical gymnasium. His mathematical interests soon prevailed, though in a multifaceted setting, in Germany known as ‘Bildung.’ Classical languages were no problem; philology had charms of its own. Planck equally performed on the piano. At age 16 he enrolled at the University of Munich as a student of physics with mathematics and chemistry as minors. Planck followed courses on general physics by Wilhelm Beetz and more particularly on the mechanical theory of heat, by Philipp von Jolly; the notes he took survived. In 1877-1878 he attended courses of Helmholtz and Kirchhoff at the University of Berlin. A lifelong friendship with Helmholtz was the result. More consequential—that is: from a scientific point of view—were his readings of Rudolf Clausius’ chef-d’œuvre *Abhandlungen über die mechanische Wärmetheorie* (1864-1867). Planck devoted his ‘Inaugural dissertation’ to the Second Law; entropy kept on fascinating him ever since. Attempts to contact Clausius failed; Clausius wasn’t really a man to socialize, it appeared. Undeterred, Planck, in his habilitation lecture (1880), addressed the principles of what he called the ‘mechanische Gastheorie.’ In 1885 he was—with some help by his father—nominated at the University of Kiel. The courses he came to conduct addressed electricity, optics, and ‘mechanische Wärmetheorie.’ There were echos of Heinrich Hertz’ recent discoveries on the refraction of electromagnetic radiation—waves, apparently—, while there was even chemical thermodynamics in the air. In 1888, then, he was nominated, doubtless through Helmholtz’ protection, at the University of Berlin as the successor of Kirchhoff—quite a move for a young scholar!—, and became

the director of the newly established Institute for Theoretical Physics, in the main building of the University at Unter den Linden, not too far from the almost brandnew Physikalisch-Technische Reichsanstalt, at Charlottenburg. It was the year that Clausius passed away, while seeing a new version of his *Abhandlungen* [...] through

▼ FIG. 1:  
Max Planck (ca. 1930).  
Picture made by  
Lotte Meitner-Graf  
(courtesy: Lotte  
Meitner-Graf - Archive;  
[www.LotteMeitner-Graf.com](http://www.LotteMeitner-Graf.com)).



the press; with Carl Pulfrich, a student of Clausius, Planck generously stood in and did what remained to be done, viz., the edition of the third volume, the one devoted to the kinetic theory of gases [1]. Planck and Pulfrich added what Clausius had hinted at, namely Maxwell's statistics. Graphics were still rare. One of the first to include a diagram was Oskar Meyer, in his monograph *Die kinetische Theorie der Gase* (1877), the title of which would become synonymous with a whole branche of physics (Fig.2). At the time, this was essentially *theoretical* physics; the proof for its well-foundedness had to wait for 1920 (Otto Stern). As it happened, though, similar curves showed up in thermal radiation phenomena. No wonder, then, that these were associated with gas theory and statistics (Vladimir Michelson; Wien).

### Berlin: black body-radiation and statistics

Kirchhoff's radiating 'schwarze Körper'—only radiation, perfect absorption—, initially a theoretical construct, became of practical importance when light sources had to be standardized at the P.-T.R., Berlin. The question to be answered: should the city of Berlin be illuminated by gas or electricity? If electricity, what kind of lamp was to be preferred? Planck, a frequent visitor, got involved when the first high-precision radiation isotherms became available (Fig.3). Wilhelm Wien, of the P.-T.R.-staff, had claimed a relation between the temperature of the radiation source and the wavelength at its curve's maximum,  $\lambda_{max} \cdot T = const.$  Wien also weighted the eventual statistical implications of radiation phenomena, as so strongly suggested by the modalities of the curves, typical skew distributions (1896). It was reserved for Max Planck to find the lacking pieces of the puzzle: the mathematical function behind the curves as an application of *permutation theory* and, the latter's very essence, the appropriate unit.

Planck's successive deductions are too well known to be repeated here. Let it suffice, in the present context, to give the adapted function, as published in Planck's epochal 1901 paper, 'Über das Gesetz der Energieverteilung im Normalspektrum' [2]:

$$U = \frac{8\pi c h}{\lambda^5} \cdot \frac{1}{e^{ch/k\lambda T} - 1}$$

which defines the energy distribution  $U$  as a function of  $\lambda$ . This inverse fifth-power law, which comes close to one proposed earlier by Wien, features a constant  $h$ , that needs our particular attention, since Planck's calculation of it—through a transcendent equation—left much to be desired, to say the least. Here we shall present a kind of short-cut.

### Gases and radiation

For someone thoroughly familiar with the kinetic theory of gases, the calculation of the translation velocity of molecules in the gaseous state was straightforward, that is, since 1848, when James Prescott Joule did so for hydrogen gas; his outcome had been 1899 m·sec<sup>-1</sup> for hydrogen gas at 15,6 °C and 1 atm. Clausius, in 1857, first derived the general gas law [1]:

$$pV = \frac{1}{3}nmv^2 \tag{1}$$

in which  $p$  stands for pressure,  $V$  for volume,  $n$  for the number of molecules of mass  $m$  and velocity  $v$ . In the light of the Boyle-Gay-Lussac law ( $pV = T \cdot const.$ ) Clausius subsequently wrote for the total kinetic energy of his  $n$  molecules:

$$\frac{1}{2}nmv^2 = \frac{3}{2}T \cdot const. \tag{2}$$

where  $T$  is the absolute temperature. This expression features only measurable quantities, except for the velocity,  $v$ . With the product  $nm$  as the weight  $q$ , and  $g$  as the gravitational constant Clausius obtained:

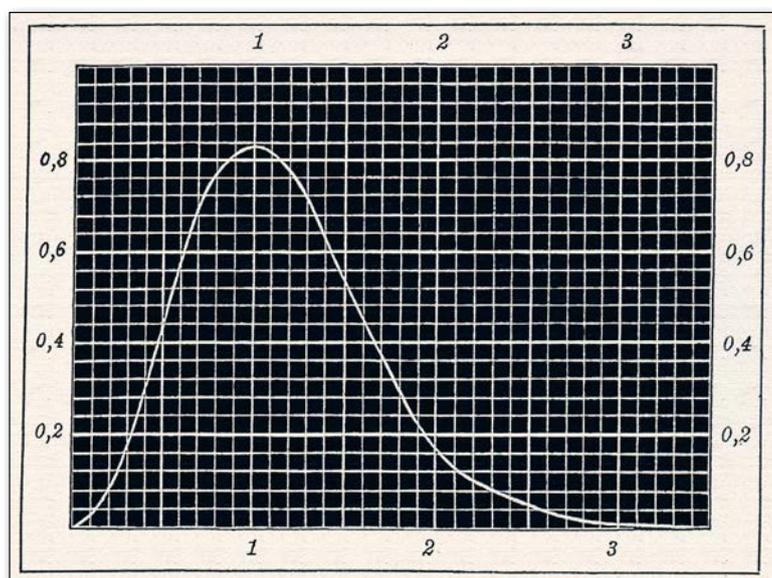
$$v^2 = \frac{3gpV}{q} \tag{3}$$

With the help of the numerical values of the constants involved this expression may be rewritten to become:

$$v = 485 \sqrt{\frac{T}{273 \cdot \rho}} \tag{4}$$

Hence, the 'mean velocity' of the molecules of a gas at temperature  $T$  can be calculated from its density at that temperature. Clausius, then, calculates the 'mean velocity' at  $T = 273$  K for the molecules of oxygen (461 m·sec<sup>-1</sup>), nitrogen (492 m·sec<sup>-1</sup>) and hydrogen (1.844 m·sec<sup>-1</sup>). All this resurfaced in the third volume overseen by Pulfrich and Planck. It cannot have escaped Planck's inquisitive mind that the reverse calculation was also interesting: when from other sources the 'mean velocity' of a gas' molecules was known, its density  $\rho$

▼ FIG. 2: A generalized curve – one of the first in print! – representing the skew distribution function  $y = \frac{4}{\sqrt{\pi}} x^2 e^{-x^2}$  for translation velocities in the gaseous state in the spirit of Maxwell. The 'most probable velocity' is chosen as the unit (from: O.E. Meyer, *Die kinetische Theorie der Gase*, 1877).



could be calculated, e.g. for 'theoretical' gases. One of the great experimental achievements of the time, then, was the measurement of the speed of light,  $c$ , with ever growing precision (Michelson and Morley; 1887 and later). Planck worked in C.G.S. terms and used a value of  $3 \cdot 10^{10}$  cm·sec<sup>-1</sup>. So we may expect him to have calculated, a blue Monday, the 'density' of light considered as a 'gas'. In the same spirit we may expect him to have calculated the 'relative weight' of the light 'molecules' involved, that is, with respect to hydrogen, a standard procedure in contemporary chemistry, which he followed as to its thermodynamic aspects. Importantly, the 'molecular' theory of light had a long history: both Newton and Laplace and the latter's followers had been molecularists, so to speak.

### A new constant, a *calculatio crucis*

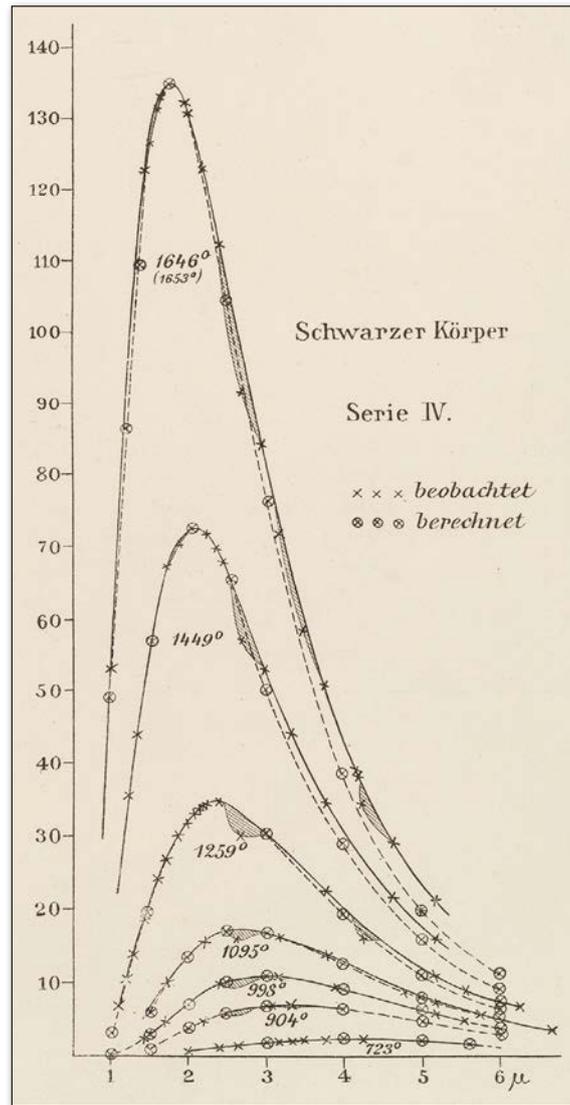
The moment that the *absolute* weight of hydrogen molecules was known, the same quantity could be calculated for all other molecules, real or theoretical, from their velocities. In this connection the *number* of molecules per cm<sup>3</sup> at 273 K, and 1 atm is crucial. Clausius had guesstimated that number, symbol  $N$  at the time, at  $3,7 \cdot 10^{19}$  (1885). Given the density of hydrogen as  $8,9551 \cdot 10^{-5}$  g·cm<sup>-3</sup> (273 K, 1 atm) the mass of one hydrogen molecule, then, comes up to  $8,9551 \cdot 10^{-5} / 3,7 \cdot 10^{19} = 2,42 \cdot 10^{-24}$  g. Supposing that, at the same  $T$ , the averaged kinetic energy of gas molecules is the same whatever the gas, we may posit, in C.G.S. units, that the energy of light 'molecules' will be equal to

$$2,42 \cdot 10^{-24} (1844 \cdot 10^2)^2 = 8,23 \cdot 10^{-14} \text{ erg}$$

On the other hand, that energy must vary directly as the frequency of the light in question. In terms of the radiation curves this is the 'most probable frequency', the one of the curve's maximum. The most reliable data of the moment were those of Lummer and Pringsheim (1899; cf. Fig.3). For a radiating black body of temperature  $T$  and  $\lambda_{max}$  as the 'most probable wavelength', Lummer and Pringsheim had established that the product  $\lambda_{max} \cdot T$  of Wien's law was 0,294 cm·degree. At  $T = 273^\circ$  abs., therefore,  $\lambda_{max} = 1,077 \cdot 10^{-3}$  cm, which corresponds to a frequency  $f = 3 \cdot 10^{10} / 1,077 \cdot 10^{-3} = 2,79 \cdot 10^{13}$  sec<sup>-1</sup>. We thus need a proportionality constant, Planck's future eponyme, of

$$8,23 \cdot 10^{-14} / 2,79 \cdot 10^{13} = 2,95 \cdot 10^{-27} \text{ erg·sec}^{-1}.$$

Considering that the energy of a light 'molecule' corresponds to  $3kT$ , the proportionality constant, later to be called after Boltzmann, appears to be  $8,23 \cdot 10^{-14} / 3 \cdot 273 = 9,75 \cdot 10^{-17}$  erg·K<sup>-1</sup>. Since the universal gas constant  $R$  for a quantity of a gas corresponding to one 'g-Molecül' — Planck's term, borrowed from



◀ FIG.3: Lummer and Pringsheim 1899 [3]: radiation curves for temperatures from 723 up to 1646° abs.;  $\lambda$  is expressed in  $\mu$  ( $10^{-4}$  cm). Do notice that the curves do not intersect, not unlike the isotherms to be expected in the kinetic theory of gases.

thermochemistry — was known to be  $8,3 \cdot 10^7$  erg·K<sup>-1</sup> we get for the number of molecules in such a 'g-Molecül'  $8,3 \cdot 10^7 / 9,75 \cdot 10^{-17} = 8,5 \cdot 10^{23}$ . Quite some other constants are now within reach, e.g. the unit charge of electrons and ions.

These numerical values for the searched constants are slightly at variance with those of Planck ( $h = 6,55 \cdot 10^{-27}$  erg·sec;  $k = 1,346 \cdot 10^{-16}$  erg·K<sup>-1</sup>;  $6,175 \cdot 10^{23}$  per g-Molecül).

Importantly, the Joule-Clausius-Maxwell line of reasoning taken over by Planck could also be applied to other novelties such as 'electrons'. Joseph John Thomson (1907), for instance, having established that the mass of an electron is  $2,6 \cdot 10^{-27}$  gram, calculated in this way their translation velocity in a conductor, taking  $v_{hydrogen} = 1700$  m·sec<sup>-1</sup> at 273 K: his outcome was about  $10^5$  m·sec<sup>-1</sup>. Much later, in 1934, Enrico Fermi similarly calculated the 'thermal velocity' of neutrons at room temperature ( $2.600$  m·sec<sup>-1</sup>).

<sup>1</sup> To be compared with Sommerfeld's values in the range of  $2.4 \cdot 10^{-27}$  and  $1.4 \cdot 10^{-28}$  erg·sec for  $\gamma$ - and  $\beta$ -rays and  $8 \cdot 10^{-27}$  erg·sec for Röntgen's rays [4].

## The Nobel Prize

The Great War had toppled the procedures of the Nobel Foundation. So it came that nominations for three years in a row— 1917, 1918 and 1919—were addressed in 1919. Max Planck, then, was awarded the Nobel Prize for Physics of 1918; it was handed over in 1920. He received it, as the Selection Committee summarized its arguments, “in recognition of the service he rendered to the advancement of Physics by his discovery of energy quanta”. Among the nominators was Albert Einstein, who, in his letter of October 1918, stressed the importance of Planck’s innovations i.a. for Niels Bohr’s theory of the relation between spectra and atomic structure. Arnold Sommerfeld referred, on 20 December 1917, to his own work on the new constant for Röntgen’s rays, just to show the viability of Planck’s approach, but, he too, mentioned Bohr: if Bohr was an obvious candidate for the near future, Sommerfeld argued, he ought to be preceded by Planck. Wilhelm Wien proposed for the same year both Planck and Bohr, in that order; Heinrich Rubens suggested to award the prize to Planck and Bohr together. There were others (Leo Graetz, Carl von Linde and Edgar Meyer), who stressed the importance of Planck’s quanta in the study of specific heat at low temperatures, as conducted by Walther Nernst. In all these letters there is, naturally, some window-dressing at stake. The most trustful as to the historical context appears to have been Max Born, in a long letter, dated 20 November 1918. Born indeed recognizes the crucial role of Wien’s statistical interpretation along Maxwellian lines (1896), its failure for longer wavelengths, Planck’s new formula (based on Boltzmann’s use of permutation-theory), and the indispensable energie-elements.

## Acknowledgment

I am indebted to Karl Grandin (Royal Swedish Academy of Sciences, Stockholm; Chair EPS-HoP Group) for kindly allowing me to consult the letters nominating Planck for the the 1918 and 1919 Nobel Prize for Physics. For documentary photography I am obliged to Tony Barrett (Lotte Meitner-Graf Archive, Cambridge) and Dirk Fennema (University of Groningen).

## About the author



**Henk Kubbinga** is a historian of science at the University of Groningen and member of the EPS-HoP-Group. Actually he is finishing the fifth and last volume of *The collected papers of Frits Zernike* (1888-1966).

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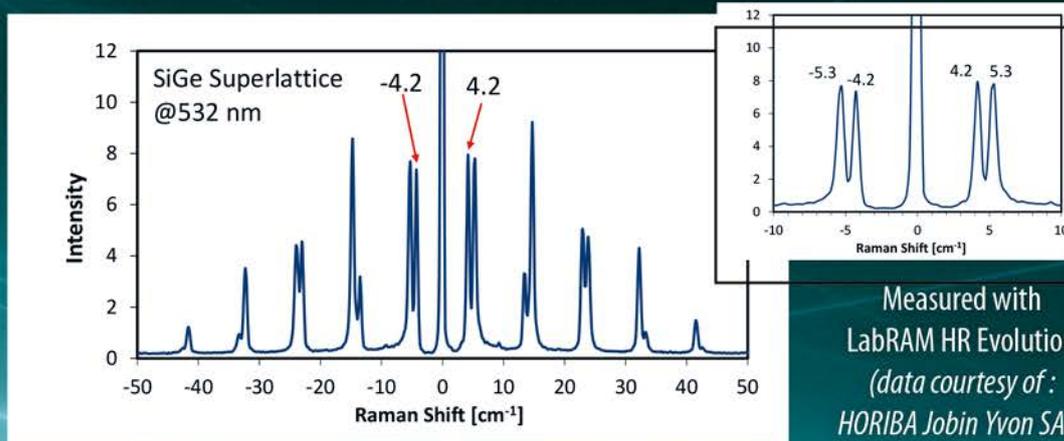
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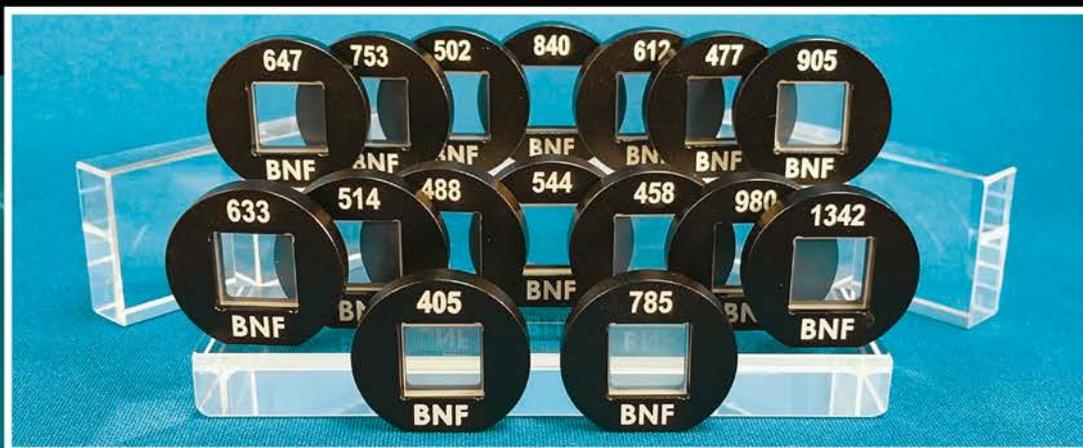
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