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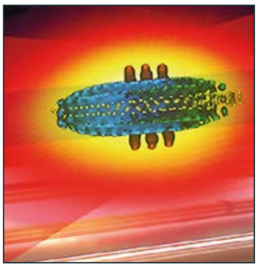
Cover picture: © iStoclPhoto, see p.21 nature's engines: active matter.



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Nature's engines: active matter

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A brief tour of the climate machine


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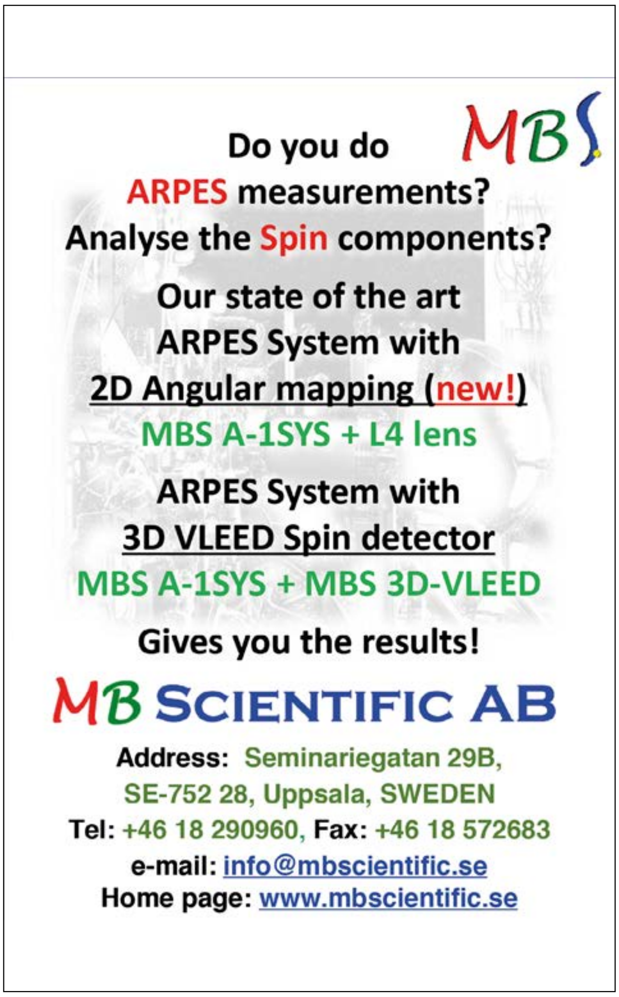
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[EDITORIAL]

Scientific and ethical responsibility

The different recent statements by President Trump raise a lot of questions and anxieties in the US but also outside the country. In his first address to Congress at the end of February he outlined in his priorities a sharp increase in military spending at the expense of foreign aid and environmental programmes. "This budget will be a public safety and national security budget," Trump said at the White House and "will put America first".

Scientists employed or funded by the US Environmental Protection Agency (EPA), the National Institutes of Health (NIH), and other federal agencies are now awaiting official words on the proposed budget cuts, typically 10%, which can have dramatic effect on environment, public health, education and science funding. What else will come up after the earlier announcement on immigration restrictions that generated so many reactions worldwide? An Open Letter was sent by EuroScience calling upon European governments and the European Commission "to uphold the principles and values that underpin scientific progress, to work with their counterparts in the US administration to maintain a global science system based on these principles and to take any measure at the national and European levels to preserve and increase the world's scientific and research capacity". EPS is one of the cosignatories of this letter. We stated officially that "Science was and will never be restrained by physical, cultural and political barriers. In our globalized world, where international scientific collaboration (*e.g.*, at large-scale facilities such as CERN) has become the rule, there is no place for discrimination and censorship. Any measure that restricts the freedom of movement and communication of our US colleagues will have a profound impact on science and innovation in Europe and other continents".

This brings us to the responsibility of scientists in dealing with policy and ethical matters, which might be outside their every day's concerns but can have a large impact on their funding sources and simply the future of their career. Indeed, it is not excluded that the budget cuts proposed in the US can trigger similar developments in Europe. For these reasons we have to remain vigilant and willing to come out of our labs to have our opinions heard. A good example is the Scientists' March on Washington that will take place on April 22 with the expectation of sister rallies taking place around the globe. "It is time for scientists, science enthusiasts, and concerned citizens to come together to make ourselves heard!" can be read on the official webpage of the organizers. The event is "a celebration of our passion for science and a call to support and safeguard the scientific community". The following weekend, environmentalists are planning a massive climate change march.

All this happens based on Newton's third law stating that for every action there is an equal and opposite reaction!

Science was and will never be restrained by physical, cultural and political barriers.

It is also interesting to read under the official link of the Union of Concerned Scientists www.ucsusa.org that "throughout its history, UCS has followed the example set by the scientific community: we share information, seek the truth, and let our findings guide our conclusions". In this way it was able to build a reputation for fairness and accuracy and amassed an impressive history of accomplishments.

Last year EPS was consulted by ALLEA, the All European Academies, in its task to review and update the European Code of Conduct for Research Integrity. We responded positively as EPS fully agrees with such principles as honesty in communication, impartiality and independence, objectivity, openness and accessibility, reliability in performing research, duty of care and responsibility for future generations of scientists. Even if these rules are meant to prevent fraudulent activities within the scientific community, it is also our basic responsibility to provide answers to global challenges, engage in social and economic debates and finally guide decisions that shape our societies. EPS is and should remain a strong advocate of these ideas.

After two years of an extraordinary experience as president of the European Physical Society, it is time to pass the torch to my successor, Rüdiger Voss, with all my best wishes for a successful presidency. ■

Christophe Rossel,
EPS President

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EPS HISTORIC SITES

Piersanti Mattarella Tower of Thought

Erice, Sicily, Italy

The EPS Historic Site Award commemorates places in Europe that have played an important part in the historical development of Physics. On August 21st 2016 the "Piersanti Mattarella Tower of Thought" at the Ettore Majorana Foundation and Centre for Scientific Culture (EMFCSC) in Erice, Sicily, was inaugurated as the 30th EPS Historic Site by Prof. Jan Szyszko, Minister of Environment of the Republic of Poland.

The unveiling of the EPS Historic Site plaque took place at the base of the tower in the presence of Antonino Zichichi, President of the EMFCSC, Luisa Cifarelli, President of the Italian Physical Society and Chair of the EPS Historic Sites Committee, Sergio Bertolucci, former Director of Research and Scientific Computing at CERN, Horst Wenninger, past Research-Technical Director at CERN and myself, as a member of the Blackett Laboratory at Imperial College London. The ceremony coincided with the 49th Session of the International Seminars on Planetary Emergencies whose participants were also in attendance.

The EMFCSC was founded in 1962 by the Italian physicist Antonino Zichichi, who has served as director of the Centre to the present day.

The Tower of Thought owes its name to the source of inspiration provided by the study at the top of the tower to visiting scientists including

▾ The unveiling of the EPS Historic Site plaque. From left to right: H. Wenninger, M.J. Duff, L. Cifarelli, J. Szyszko, A. Zichichi, S. Bertolucci. (Credits: EMFCSC)

Nobel Laureates Rudolf Mössbauer, Kenneth Wilson, Richard Feynman, Georges Charpak, Samuel Ting, Wolfgang Pauli, Norman Ramsey, Frank Wilczek, Gerardus 't Hooft, Alex Müller and Masatoshi Koshiba and other leading thinkers such as John Bell. The Tower was also the venue of the 1982 Erice Statement for a science without secrets and without frontiers devised by Paul Dirac, Piotr Kapitza and Antonino Zichichi.

Piersanti Mattarella, assassinated by the Mafia in January 1980 while he held the position of President of the Regional Government of Sicily, was a strong advocate for the EMFCSC. He was the brother of Sergio Mattarella, the current President of the Italian Republic.

Professor Antonino Zichichi was an extraordinary student of Lord Patrick Maynard Stuart Blackett. The current Physics department building of Imperial College is named the Blackett Laboratory.

In April 2014 the Blackett Laboratory was a recipient of the EPS Historic Site Award and at the Erice ceremony I took the opportunity to say few words about the links between the Blackett Lab and the EMFCSC.

▲ Piersanti Mattarella Tower of Thought.

Nino holds Blackett in high regard and you will find in Erice the Blackett Lecture theatre where the prizes for the best students of the Erice Subnuclear Physics School include the Blackett Diploma. So we were delighted when Prof Zichichi accepted our invitation to the award ceremony at Imperial College to deliver the distinguished lecture entitled 'My testimony on Lord Patrick M S Blackett."

So I was grateful to Professor Zichichi for reciprocating the hospitality and inviting me to this Piersanti Matarella ceremony to celebrate Blackett's legacy in both London and Sicily and in recognition of the common scientific and cultural interests of the Blackett Lab and the EMFCSC. ■

Michael Duff
Emeritus Professor of Physics
and Senior Research Investigator
Blackett Laboratory

INTERNATIONAL DAY OF WOMEN AND GIRLS IN SCIENCE

On 15 December 2015, the United Nations General Assembly adopted resolution A/RES/70/212 declaring 11 February as the *International Day of Women and Girls in Science*. The United Nations invites all Member States including academia, individuals and society in general, to observe the International Day of Women and Girls in Science to promote the full and equal participation of women and girls in education, training, employment and decision-making processes in the sciences.
In Spain a group of men and women, researchers, scientific communicators and teachers, took on the challenge. Some are members of the "Royal Spanish Physics Society" and other institutions, although they all participated as individuals to start the February 11 Initiative. The initiative is based on the belief that a broad knowledge of the work of women scientists, past and present, will produce role models for future women researchers and hence will help close the persistent gender gap in science. The initiative has attracted further participation by individuals, associations and organisations and is already attracting the attention of Spanish media.
The role of the February 11 Initiative is to promote the organisation of activities for students and for the general public and to publicise them. This involves the creation of a webpage 11defebrero.org (in Spanish), gathering information about the achievements of women scientists, the situation of girls and women in science, and all the activities that are being organised mainly in Spain. The initiative is also in twitter *@11defebreroES*, facebook *@dia11defebrero* and instagram *11defebreroes*.
The event took place for the first time in 2017 and included many activities mostly between the 6th and 19th of February. The initiative will hopefully be consolidated in the coming years. The number of activities is still growing and so far they include visits and activities in scientific institutions, seminars in secondary schools, theatre displays, outreach talks in cultural centres and bars, and TV programs. Anyone in Spain interested in joining the initiative by organising activities is most welcome to contact the coordinators. Institutions and organisations across Europe are also invited to join the celebration of the International Day of Women and Girls in Science.■

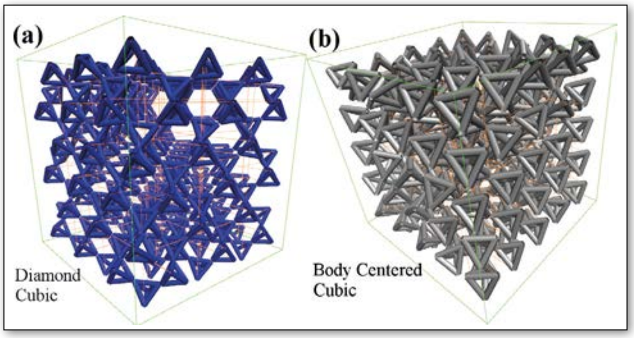
Martine Bosman (IFAE)

Highlights from European journals

LIQUID PHYSICS

How water can split into two liquids below zero

Theoretical possibility of the coexistence of dual liquid states of matter in sub-zero water due to the origami-like stacking behaviour of microscale molecules



▲ Representation of the diamond lattices formed by the particle studied.

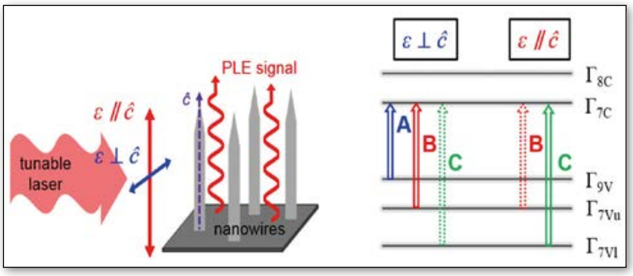
Did you know that water can still remain liquid below zero degrees Celsius? It is called supercooled water and is present in refrigerators. At even smaller temperatures, supercooled water could exist as a cocktail of two distinct liquids. Unfortunately, the presence of ice often prevents us from observing this phenomenon. So physicists had the idea of replicating the tetrahedral shape of water molecules—using DNA as a scaffold to create tetrahedral molecules—and thus removing the interference of ice formation. This approach allowed the authors to confirm that, in theory, a dual liquid phase is possible in sub-zero water and any other liquids made of tetrahedral molecules. These results have been published recently. It is a great tale of how the underlying microscopic shape determines the overall macroscopic form. ■

■ **S. Ciarella**, **O. Gang** and **F. Sciortino**,
'Toward the observation of a liquid-liquid phase transition in patchy origami tetrahedra: a numerical study, *Eur. Phys. J. E* **39**, 131 (2016)

MATERIAL SCIENCE

Electronic properties of III-V nanowires unveiled

Semiconductor nanowires (NWs) are technologically relevant structures in the field of Nanoscience. The name 'nanowires' is due to their geometrical characteristics: NWs have two dimensions in the range of tens of nanometers and a third dimension in the micrometre range. The filamentary shape and nanoscale diameter of NWs have rendered them versatile and cost-effective components of technological devices. Moreover, in NWs novel properties arise compared to their bulk counterparts due to size-dependent effects. A careful determination of NW properties is thus necessary for achieving the best design of devices, as well as for explaining fascinating physical effects in NWs.



▲ Geometry of the experiment (left) and optical selection rules in wurtzite crystals (right).

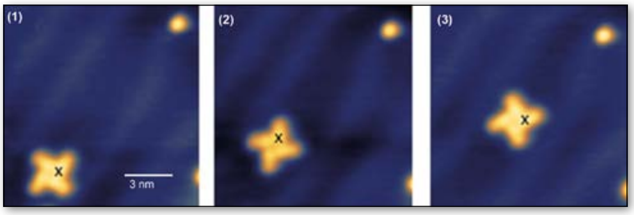
Since standard absorption spectroscopy is hard to perform in NWs due to their small volume, we use an alternative technique, photoluminescence excitation spectroscopy (PLE), to assess the electronic properties of III-V NWs. Specifically, we shine light on the debated band structure of wurtzite GaAs and InP NWs employing polarization-resolved PLE. Moreover, PLE is used as a statistically-relevant method to identify wurtzite and zincblende NWs in a same InP sample. Finally, resonant excitonic effects in the density of states of $In_xGa_{1-x}As$/GaAs core/shell NWs are highlighted by high-resolution PLE. ■

■ **M. De Luca**,
'Addressing the electronic properties of III-V nanowires by photoluminescence excitation spectroscopy',
J. Phys. D: Appl. Phys. **50**, 054001 (2017),

APPLIED PHYSICS

The Dresden Training for the International nanoCar race

To prepare its participation to the first international nano-car race in Toulouse (France) Spring 2017, the Dresden Team exercised on the Toulouse LT-UHV 4-STM reconfigured for the race with 4 independent controllers (one per scanning tunneling microscope (STM)). An Au(111) surface was prepared over a full gold substrate. A 90 nm long race track with two turns was



▲ A 3 step driving along the Au(111) track. The black cross indicates the tip position for the inelastic tunneling excitation of the Dresden molecule-vehicle.

selected on this surface following the rules (www.cemes.fr/Molecule-car-Race). The Dresden windmill molecule-vehicles were deposited in ultrahigh vacuum conditions, imaged, and manipulated by any one of the 4 tips on race track reaching a 5 nm per hour driving speed,-including the STM image recording after each driving bias voltage pulse. Strategies for a safe and fast driving were established by the Dresden team along the Au(111) surface fcc rafter together with the possibility to repair crashed molecules, for example during the negotiation of a turn. The teams registered for the nano-car race will benefit from this atomic-scale, single-molecule-vehicle driving experience to improve their own driving strategy. ■

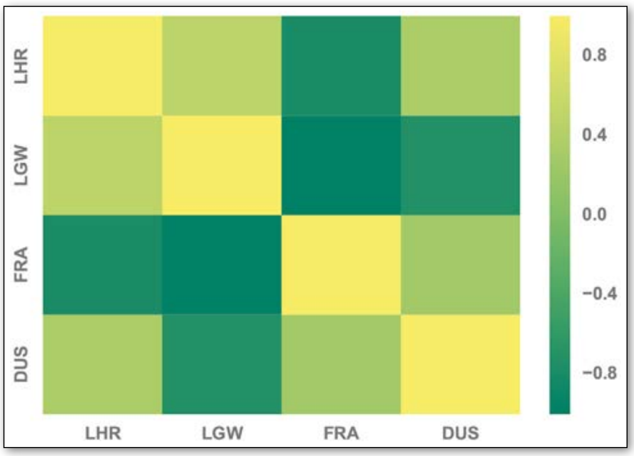
■ **F. Eisenhut**, **C. Durand**, **F. Moresco**, **J.-P. Launay** and **C. Joachim**,
'Training for the 1st international nano-car race: the Dresden molecule-vehicle', *Eur. Phys. J. Appl. Phys.* **76**, 10001 (2016).

COMPLEX SYSTEMS

Functional Multiplex PageRank: **the centrality is a function**

Multiplex networks are formed by a set of nodes connected by different types of interactions. The centrality of a node in a multiplex network depends on the influence one attributes to different types of connections. For example consider a multiplex of two layers formed by Lufthansa and British Airways flights. If we attribute maximum influence to Lufthansa flights Frankfurt airport is more central than Heathrow airport while the opposite is true if we attribute maximum influence to British Airways flights. The Functional Multiplex PageRank combines this information through a paradigmatic shift: the centrality of a node is not a single number but an entire function associated to the relevance given to the different types of connections. For each node it allows to characterize which types of connections contribute the most to its centrality. Interestingly the correlations between the Functional Multiplex PageRank of different nodes reveal the similarity in the role of the nodes. ■

▼ Correlations between the Functional Multiplex PageRank of Heathrow, Gatwick, Frankfurt and Düsseldorf airports in the multiplex network formed by Lufthansa and British Airways flights.

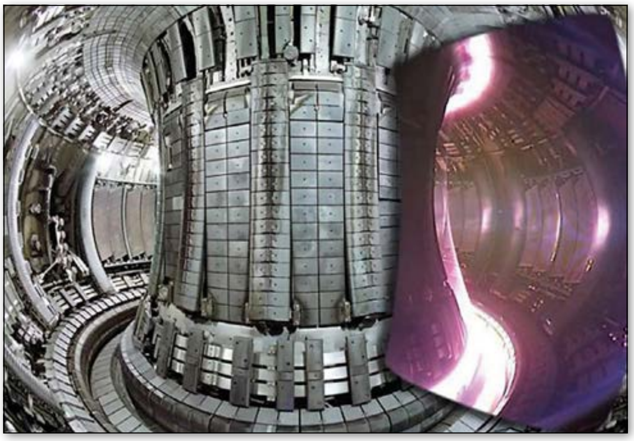


■ **J. Iacovacci**, **C. Rahmede**, **A. Arenas** and **G. Bianconi**,
'Functional Multiplex PageRank', *EPL* **116**, 28004 (2016)

PLASMA PHYSICS

How donut-shaped fusion plasmas managed **to decrease adverse turbulence**

Achieving fusion has become more realistic since plasma flow was identified as regulating turbulence in the 1980s



▲ Toroidally shaped plasmas of the tokamak type offer a path to low turbulence.

Fusion research has been dominated by the search for a suitable way of ensuring confinement as part of the research into using fusion to generate energy. In a recent paper the author gives a historical perspective outlining how our gradual understanding of improved confinement regimes for what are referred to as toroidal fusion plasmas –- confined in a donut shape using strong magnetic fields-- have developed since the 1980s. He explains the extent to which physicists' understanding of the mechanisms governing turbulent transport in such high-temperature plasmas has been critical in improving the advances towards harvesting fusion energy. Physicists found in the 1980s that toroidally shaped plasmas of the tokamak type offer a path to low turbulence thanks to their ability to self-organise. Over the course of the past 30 to 40 years, they came to realise that turbulence and plasma flow are linked and regulate each other. Indeed, they found that the spatial variation of the plasma flow regulates the turbulence of the drift-wave type. They also found that this mechanism is another example of a self-organisation process known for a long time in geophysical fluid dynamics. ■

■ **F. Wagner**,
'The history of research into improved confinement regimes', *Eur. Phys. J. H*, DOI 10.1140/epjh/e2016-70064-9 (2017)

APPLIED PHYSICS

Champagne owes its taste to the **finely tuned quality of its bubbles**

What provides the wonderful aromas is a long neuro-physico-chemical process that results in bubbles fizzing at the surface of champagne

▲ Observation of bubble nucleation in a glass of champagne using high-speed video microscopy. (Photograph by Hubert Raguet)

Ever wondered how the fate of champagne bubbles from their birth to their death with a pop enhances our perception of aromas? These concerns, which are relevant to champagne producers, are the focus of a special issue of *EPJ Special Topics*, celebrating the 10th anniversary of the publication. Thanks to scientists, champagne producers are now aware of the many neuro-physico-chemical mechanisms responsible for aroma release and flavour perception. The taste results from the complex interplay between the level of CO_2 and the agents responsible for the aroma--known as volatile organic compounds--dispersed in champagne bubbles, as well as temperature, glass shape, and bubbling rate. In the first part of the Special Topic issue, a model is presented to describe, in minute detail, the journey of the gas contained in each bubble. The second part of this Special Issue is a tutorial review demystifying the process behind the collapse of bubbles. It is mainly based on recent investigations conducted by a team of fluid physicists from Pierre and Marie Curie University, in Paris, France. ■

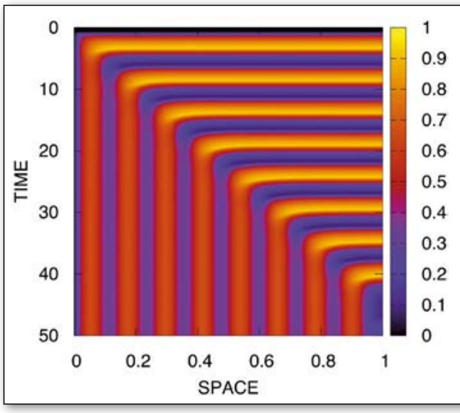
■ **G. Liger-Belair** and **T. Séon**,
'Bubble Dynamics in Champagne and Sparkling Wines: Recent Advances and Future Prospects', *Eur. Phys. J. ST* **226** Issue 1 (2017).

COMPLEX SYSTEMS

Pattern formation induced by fixed boundary condition

Pattern formation in nonequilibrium systems has been extensively investigated in physical and chemical systems as well as for biological morphogenesis, since the seminal study by Alan Turing: How perturbations to uniform, stationary states are amplified to form a spatially periodic pattern is thoroughly understood with extensive experimental demonstrations. In contrast to this spontaneous pattern formation, however, little is understood how given boundary condition leads to global pattern formation. Here, we demonstrate that the fixed boundary can transform a temporally-periodic, spatially-uniform state to a spatially-periodic, stationary pattern– a novel class of pattern formation mechanism. This pattern formation is not understood by the Fourier-mode linear stability analysis – the standard tool for Turing instability. Rather, by introducing a one-dimensional 'spatial' map, the emergent pattern is reproduced well as its periodic attractor, by replacing the time with space. Accordingly, linear dispersion relationship between the period and wavelength is obtained. This provides a general tool to analyze the pattern formation in reaction-diffusion systems, while the boundary-induced pattern formation mechanism will explain several biological morphogenesis, including recent experimental observations. ■

■ **T. Kohsokabe** and **K. Kaneko**,
'Boundary-induced pattern formation from temporal oscillation: Spatial map analysis', *EPL* **116**, 48005 (2016).

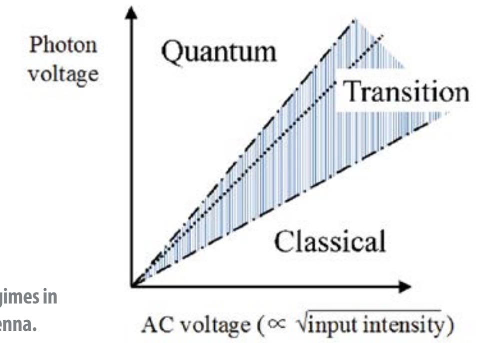


◀ Time development of the reaction diffusion dynamics. Fixed boundary condition at x=0 transforms uniform temporal oscillation to stationary periodic pattern.

APPLIED PHYSICS

Operating regimes in an optical rectenna

Optical rectennas: where Maxwell meets Einstein



▸ Operating regimes in an optical rectenna.

Conventional semiconductor solar cells convert the solar spectrum to dc electricity, relying on the photoelectric effect. Their ultimate efficiency is limited to 44% because the entire photon spectrum is used at a voltage equal to the semiconductor bandgap. An unconventional approach is to use optical rectennas, nanoantennas with high-speed diodes. In this work we show how to break the efficiency limit using optical rectennas.

Microwave rectennas are described by classical electromagnetics and have been used for rectifying microwaves with power conversion efficiencies greater than 80%. However, the interaction of high-speed diodes with light is different than with microwaves. Instead, an optical rectenna can operate in one of three different regimes: quantum, transition, and classical.

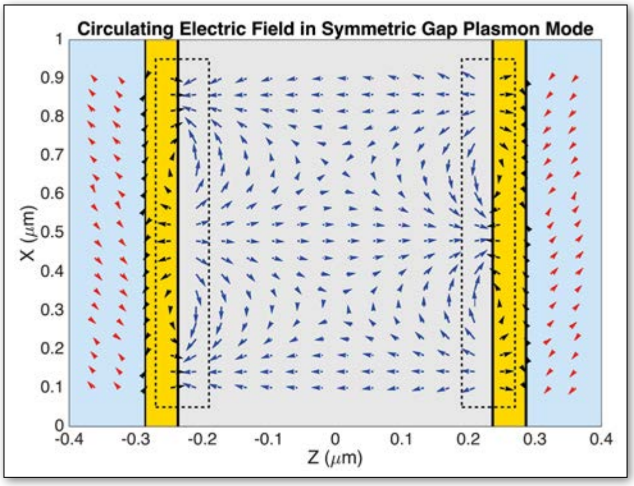
The quantum regime occurs for weak optical intensities and is subject to the 44% limit because each incoming photon is used to produce an electron at the rectenna operating voltage, as in conventional solar cells. Classical operation occurs when the intensity is strong and the photon energy is low. Here, electrons absorb multiple photons to produce current at higher voltages, as in classical rectennas, resulting in higher solar energy conversion efficiencies that ideally can exceed 80%. ■

▮ **S. Joshi** and **G. Moddel**,
'Optical rectenna operation: where Maxwell meets Einstein', *J. Phys. D: Appl. Phys.* **49**, 265602 (2016)

OPTICS

Perfect absorption with gap-plasmons enhances elusive Bellinfante's spin

Bellinfante's transverse spin angular momentum carried by structured light fields has been the subject of several theoretical and experimental investigations in recent years. This transverse spin has been labelled as "elusive" because of its minute magnitude, rendering experimental detection extremely difficult. We propose a scheme involving a symmetric gap-plasmon guide under bidirectional illumination as in coherent perfect absorption (CPA) and demonstrate a noticeable enhancement of this extraordinary spin. The prerequisite for the enhancement is the coincidence of one of the coupled plasmon resonances in the structure with the frequency where CPA of the incident light occurs. The CPA mediated total transfer of incident energy to the plasmon mode augments the local field leading to the resonant enhancement of the extraordinary spin. The enhancement is robust and persists even when minor asymmetry in the structure results in non-reciprocity and disturbs the CPA. ■



▴ Rotation of the electric field vector at the inner gold-air interfaces (in the dashed rectangular boxes) in the plane of incidence. The circulating field is the source of the transverse spin. Different materials are indicated using different background colours: light blue - glass, gold - gold, grey - air.

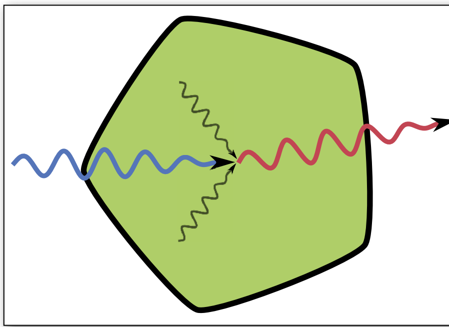
▮ **S. Mukherjee** and **S.D. Gupta**,
'Coherent perfect absorption mediated enhancement of transverse spin in a gap plasmon guide', *Eur. Phys. J. Appl. Phys.* **76**, 30001 (2016)

MATERIAL SCIENCE

Fluctuational electrodynamics for nonlinear media

Nonlinear optics gives rise to a lot of interesting phenomena like frequency mixing, the optical Kerr effect, the Raman effect, and many others. With the advent of metamaterials, (nonlinear) optical properties can nowadays be tuned, controlled, and designed, allowing for the exploration of new physics. In this article, the fluctuations of the electromagnetic field in the presence of such materials are investigated.

Fluctuational electrodynamics, combining classical electrodynamics with quantum and thermal noise, is a powerful framework to study effects which appear in equilibrium (such as



◂ Nonlinear coupling of incident waves (blue) and fluctuation-induced waves (black).

Casimir forces) as well as those found out of equilibrium (such as radiative heat transfer). So far, this concept relies on the optical linearity of the involved objects.
In this article, fluctuational electrodynamics is adapted to describe also objects with nonlinear optical response, including the amendment of the noise (so called Rytov currents). Most notably, electric currents fluctuating because of noise and induced currents due to incident waves become coupled, giving rise to new phenomena. As an example, the Casimir force between two plates with nonlinear optical properties is computed, which has a different distance dependence at close proximity compared to the linear case. ■

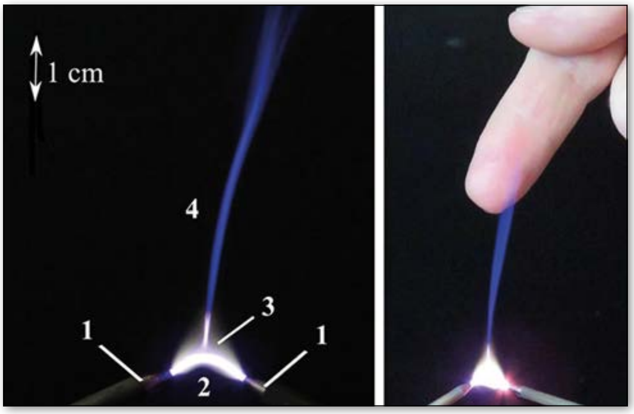
■ **H. Soo** and **M. Krüger**,
'Fluctuational electrodynamics for nonlinear media',
EPL **115**, 41002 (2016)

PLASMA PHYSICS

Novel plasma jet offshoot phenomenon explains **blue atmospheric jets**

Russian physicists identify mysterious right-angle side-jet occurring off the plasma arc in air at ambient pressure conditions

Ionised matter, like plasma, still holds secrets. Physicists working with plasma jets, made of a stream of ionised matter, have just discovered a new phenomenon. Indeed, the authors found a



▴ Example of the apokamp effect in a plasma jet.

new type of discharge phenomenon in an atmospheric pressure plasma. It has been dubbed apokamp—from the Greek words for 'off' and 'bend', because it appears at a perpendicular angle to where plasma jets bend. Their findings have been recently published and are particularly relevant for the development of novel applications in medicine, health care and materials processing because they involve air at normal atmospheric pressure, which would make it cheaper than applications in inert gases or nitrogen. This phenomenon can help explain the blue jet phenomenon identified in 1994 in the upper atmosphere, where strange upwards-facing jets develop from thunderstorm clouds. ■

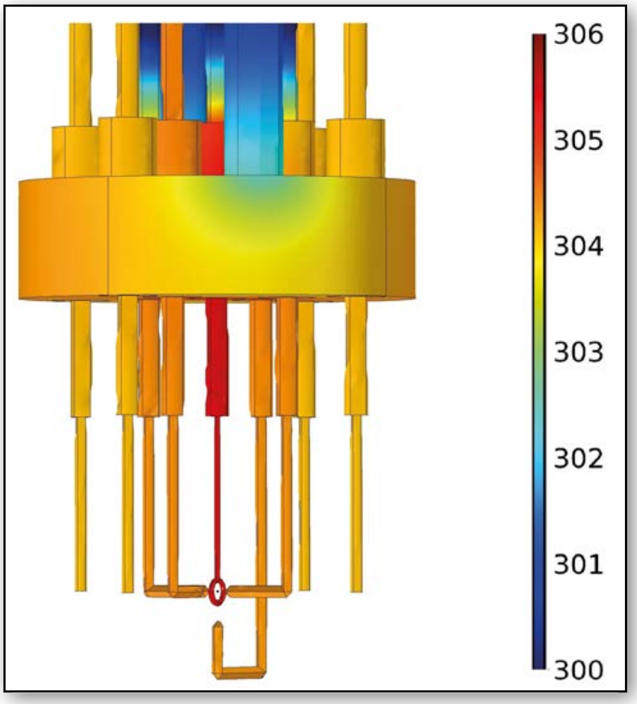
■ **E.A. Sosnin**, **V.A. Panarin**, **V.S. Skakun** , **E. Kh. Baksht** and **V.F. Tarasenko**,
'Dynamics of apokamp-type atmospheric pressure plasma jets', *Eur. Phys. J. D* **71**, 25 (2017)

APPLIED PHYSICS

Accurately evaluating on $^{40}Ca^+$ **optical clock BBR temperature**

Optical clock based on $^{40}Ca^+$ single-ion is a promising option in the program of transportable optical clocks. In such system, one of the largest contributions to the systematic uncertainty is blackbody radiation (BBR) shift. The uncertainty of BBR shift is basically dependent on the uncertainty of the BBR shift coefficient and the uncertainty of temperature measurement on the trap environment which both have a contribution at 10^{-17} level in fractional frequency units. We report a careful evaluation of BBR temperature rise seen by $^{40}Ca^+$ ion confined in

▾ Modelled temperature distribution of the miniature Paul trap.



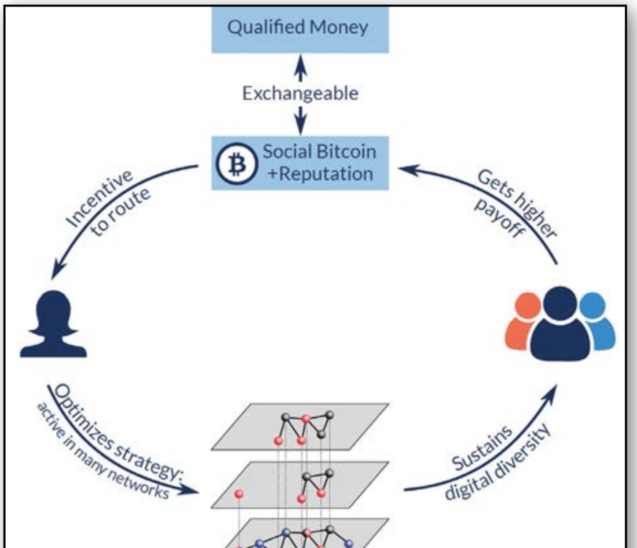
a miniature Paul trap via FEM modelling. The result indicates that the uncertainty of the BBR shift due to temperature has a contribution of 5.4×10^{-18} to the systematic uncertainty, and it allows improving the clock's overall accuracy in the future. Moreover, an interesting work has been reported on validating the finite-element temperature model by comparison with thermal camera measurements calibrated against PT1000 thermometers. This work can be used to validate the FEM model of other optical clock systems and to evaluate the temperature in a vacuum chamber measured by thermal camera. ■

■ **P. Zhang**, **J. Cao**, **H. Shu**, **J. Yuan**, **J. Shang**, **K. Cui**, **S. Chao**, **S. Wang**, **D. Liu** and **X. Huang**,
'Evaluation of blackbody radiation shift with temperature-associated fractional uncertainty at 10^{-18} level for $^{40}Ca^+$ ion optical clock', *J. Phys. B: At. Mol. Opt. Phys.* **50**, 015002 (2017).

COMPLEX SYSTEMS

Economics made simple with physics models

Snapshot of the study of economic phenomena using the tools of physics



▲ Cover of the special issue.

How would you go about understanding how markets can suddenly be gripped by panic? To physicists, using a model originally developed to explain magnetism might make sense. Yet, economists may find this extremely counter-intuitive. Both physical and economic phenomena may possess universal features that could be uncovered using the tools of physics. The principal difference is that in economic systems — unlike physical ones — current actions may be influenced by the perception of future events. This *European Physical Journal Special* Topics issue examines the question as to whether econophysics, a physics-based approach to understanding economic phenomena, is more useful and desirable than conventional economics theories.

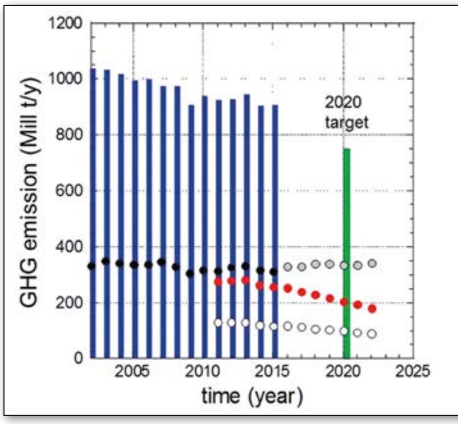
One of the features emerging from the issue is that the much coveted idea of universality may be the exception rather than the rule in the economic and the social world. Also, many of the originally proposed models of econophysics can be argued to be simplistic rather than simple. Most importantly, a clear-cut demonstration of superiority of econophysics models over standard economics models has yet to be delivered. ■

■ **S. Sinha**, **A. S. Chakrabarti** and **M. Mitra**,
'Can economics be a physical science?' *Eur. Phys. J. ST* **225** Issue 17-18 (2016)

ENERGY

100% renewable energy sources require overcapacity

To switch electricity supply from nuclear to wind and solar power is not so simple



◄ Germany's greenhouse gas (GHG) emissions from 2002 to 2015 and the political target for 2020 (bars).

Germany decided to go nuclear-free by 2022. A CO_2-emission-free electricity supply system based on intermittent sources, such as wind and solar — or photovoltaic (PV) — power could replace nuclear power. However, these sources depend on the weather conditions. In a new study published recently, the author analysed weather conditions using 2010, 2012, 2013 and 2015 data derived from the electricity supply system itself, instead of relying on meteorological data. By scaling existing data up to a 100% supply from intermittent renewable energy sources, the author demonstrates that an average 325 GW wind and PV power are required to meet the 100% renewable energy target. This study shows the complexity of replacing the present primary energy supply with electricity from intermittent renewable sources, which would inevitably need to be supplemented by other forms of CO_2 - free energy production. ■

■ **F. Wagner**,
'Surplus from and storage of electricity generated by intermittent sources', *Eur. Phys. J. Plus* **131**, 445 (2016)

PROPERTIES OF NUCLEI PROBED BY LASER LIGHT

Rainer Neugart – DOI: https://doi.org/10.1051/epn/2017201

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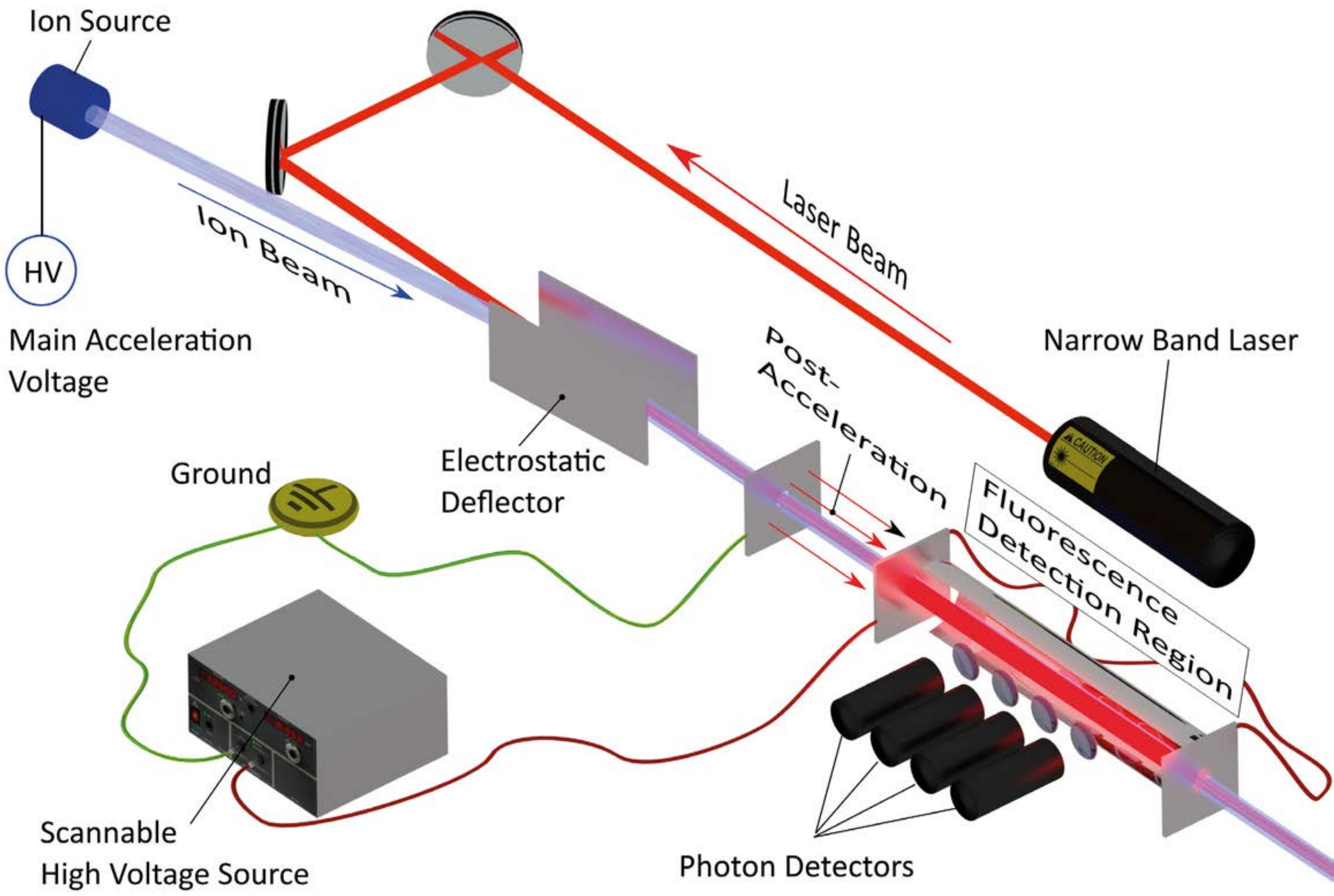
Viewing objects as small as atomic nuclei by visible light sounds quite unrealistic. However, nuclei usually appear as constituents of atoms whose excitations are indeed associated with the absorption and emission of light. Nuclei can thus interact with light via the atomic system as a whole.



Early in the past century it was discovered that basic properties of nuclei influence the atomic spectra. Energy levels of atoms with an odd number of protons or neutrons exhibit hyperfine structure [1]. This was found to arise from a nuclear magnetic moment interacting with the magnetic field produced by the shell electrons. The magnetic moment is associated with a characteristic angular momentum quantum number, called nuclear spin. Both these quantities characterize a nucleus and are related to the orbital of an unpaired nucleon.

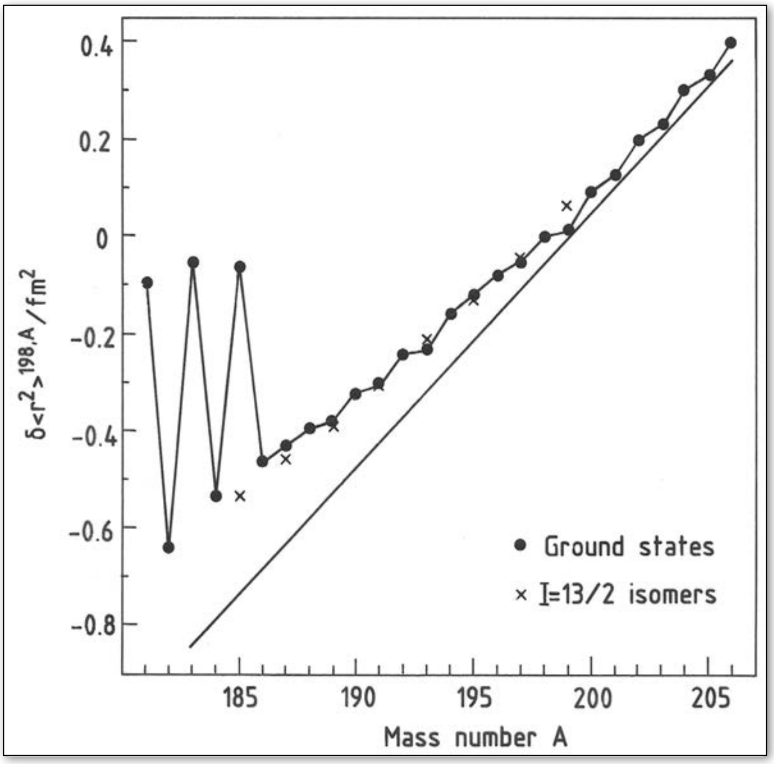
Improved spectroscopic resolution even revealed the tiny effect of a nuclear quadrupole moment interacting with the electric-field gradient from the electrons. Quadrupole moments reflect a non-spherical nuclear shape. The so-called deformation occurs by the influence of the shell structure on the collective behaviour of the nucleons. For symmetry reasons, nuclei with spin 0 or 1/2 have vanishing quadrupole moments, independent of intrinsic deformation.

Finally it was found that the wavelengths of spectral lines are slightly shifted between different isotopes. For light elements, this effect arises mainly from differences in nuclear mass. But an additional shift dominates in heavier nuclei, caused by different sizes of the nuclei influencing the Coulomb interaction between the nucleus and the electrons. More precisely, isotope shifts probe differences in the mean square nuclear charge radius $\delta\langle r^2\rangle$, a quantity which is sensitive to deformation, independently of the spin. It thus provides information complementary to the quadrupole moments.

Exotic nuclei

For about three decades, up to the seventies, a variety of magnetic-resonance experiments yielded rich data on nuclear moments of stable and some long-lived radioactive nuclei [1]. These played an important role for the development of nuclear models, in particular the shell model. Radioactive nuclei with unusual neutron-to-proton ratio came into view with the issue of stability of nuclear systems. Such nuclei also play a key role for the synthesis of elements in stellar atmospheres. The question arises whether established nuclear models are still valid for nuclei far off stability. These nuclei – sometimes called exotic nuclei – have short half-lives down to seconds or even milliseconds and can be produced only in tiny quantities. Measuring their properties requires very high sensitivity and this is where optical spectroscopy reappears on the scene, soon in combination with the new tool of tunable laser light sources.

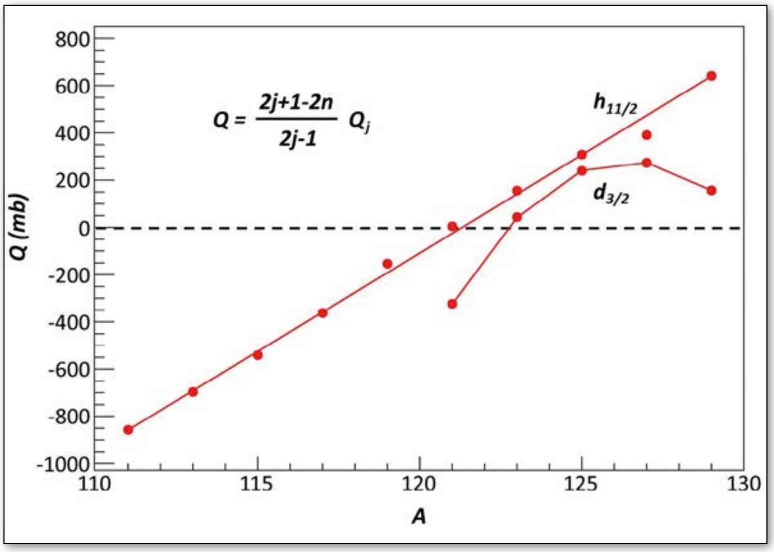
First experiments on short-lived radioactive nuclides were performed at the ISOLDE (CERN) on-line isotope separator facility, still using conventional light sources (see [2]). The spectacular results of this work on the neutron-deficient mercury isotopes (Fig. 1) boosted all further efforts enormously. From the isotope shifts in the famous 253.7 nm line, the charge radii were found to decrease gradually as expected, from the stable isotopes (like, *e.g.*, ^{202}Hg) down to ^{186}Hg. This trend continues for the even isotopes, but ^{185}Hg, ^{183}Hg, and ^{181}Hg exhibit much larger radii, comparable with the stable isotopes which have about 15 more neutrons. Theoretical considerations suggested a sudden shape change to be responsible for this effect: Depending on the even or odd number of neutrons, the nuclei are nearly spherical



▲ **FIG. 1: Development of mean square nuclear charge radii of neutron-deficient mercury isotopes (from [3]). Plotted is the difference in $\langle r^2\rangle$ between isotopes with mass number *A* and the stable ^{198}Hg.**

or strongly deformed. Both shapes even coexist in the same nucleus: ^{185}Hg has a strongly deformed spin-1/2 ground state, but a spherical spin-13/2 isomer. Very recent measurements on more neutron-deficient isotopes used the laser ion source at ISOLDE as an extremely sensitive spectroscopic tool. They show a disappearance of the strong odd-even effect beyond ^{181}Hg, confirming theoretical expectations.

The early work on mercury took advantage of large hyperfine structure and isotope shift effects. It was still based on methods of classical optical spectroscopy, limited in resolution by the Doppler broadening of spectral lines. However, most elements require much better resolution for accurate measurements of hyperfine structure and isotope shift. With tunable narrow-band cw lasers, new laser spectroscopy methods reached natural linewidth resolution in the 10 MHz range for strong optical transitions, typically two orders of magnitude below the Doppler width. On top of this comes the unbeatable sensitivity due to a high cross-section of optical resonance, given by just the wavelength: $\sigma = \lambda^2/(2\pi)$. Transitions are easily saturated with the laser power available and detection is readily achieved by counting photons from the decay of excited states. Today, the accessible spectral range covers all relevant wavelengths, from about 200 nm to 1 µm, for hyperfine spectroscopy on the isotopes of most chemical elements.



▲ **FIG. 2:** Quadrupole moments of cadmium isotopes (isomers) in the $h_{11/2}$ and $d_{3/2}$ neutron shells [9].

Nuclide production and Laser spectroscopy

A modern version of the chart of nuclides shows the enormous progress made in the exploration of the nuclear landscape and the production of nuclei far from stability. In addition to about 300 stable isotopes more than 3000 radioactive nuclei have been produced and are being investigated. Of the different production schemes we only discuss here the on-line isotope separator (ISOL) approach that has decisively influenced the implementation of laser spectroscopy techniques, in particular the ISOLDE facility [4] at CERN. Such facilities use unspecific high-energy (~ 1 GeV) nuclear reactions in a thick heated target from which the products are released and ionized. Low-energy (~ 50 keV) beams of individual isotopes are selected by magnetic mass separation and guided to different experimental stations. Using this principle ISOLDE has been an outstanding installation for nearly 50 years.

The concept of collinear laser spectroscopy [5] emerged from discussions about a suitable method to be used with ISOL beams. Such beams, obtained by acceleration in a static electric field and merged with a laser beam, naturally provide narrow Doppler width comparable to typical natural linewidths [6]. This is a consequence of the energy being proportional to the square of the velocity: Increasing all ion energies by the same amount conserves the energy spread and thus compresses the velocity distribution in the beam. The Doppler shift can be used to tune the (rest-frame) laser frequency across a resonance structure by slightly changing the velocity of the ions. The requirement of high sensitivity is met by the Doppler width matching the natural linewidth, meaning that optical resonance occurs simultaneously for all ions. Sensitivity is finally limited by the efficiency of fluorescence photon detection in the presence of background from scattered laser light. If neutral atoms offer more favourable spectroscopic conditions than singly-charged ions, the beam may be neutralized by charge exchange with alkali atoms in a vapour cell. Due to a high cross-section this process hardly affects the beam quality.

Over 30 years, collinear laser spectroscopy has provided rich information on the electromagnetic properties, radii and shapes of unstable nuclei. It is virtually impossible to show a representative choice of experimental approaches [7] and results [8]. Spins provide basic information for the classification of nuclei, while magnetic moments serve as a probe of the nuclear wave functions within a particular model. Quadrupole moments have often been interpreted qualitatively in terms of collective deformation. Nowadays, multi-configuration shell-model descriptions have succeeded to explain them on a microscopic basis, at least up to the mid-mass region approaching Z = 50.

Two recent examples

Recent measurements on the cadmium isotopes shed light on an early prediction of quadrupole moments across a complete nucleon shell. ISOLDE provides viable cadmium yields up to the "magic" neutron number N = 82, representing an excess of 16 neutrons over stable ^{114}Cd. Laser spectroscopy was performed in the Cd^+ ion [9] for the isotopic chain from ^{106}Cd to ^{130}Cd. The required laser wavelength of 214.5 nm was obtained by quadrupling the output frequency of a titanium sapphire laser.

Favourably it turns out that all odd-A nuclei from N = 63 to 81 have a spin-11/2 isomeric state. This offers the possibility of studying the unpaired neutron while gradually filling the complete $h_{11/2}$ shell. The measured quadrupole moments are shown in Fig. 2. Most striking is their perfect linear increase with neutron number, from negative to positive values. Such behaviour,

> **The question arises how well we understand the properties of nuclei far off stability, which have half-lives down to seconds or even milliseconds. Are established nuclear models still valid for nuclei with a large neutron or proton excess?**

predicted by a simple shell model, was suggested by experimental data, but never observed as beautifully. Theory will have to explain how a simple linear relationship can describe complex nuclei and why it spans 10 odd isotopes instead of 6 as would be expected for the sequential filling of the shell.

For a long time nuclear radii were interpreted in terms of phenomenological models of a deformed liquid drop of nuclear matter. These usually failed to explain details of the measured radii variations. Only for the lightest nuclei with nucleons in the lowest s and p shells microscopic approaches have now succeeded to predict the measured radii impressively well. These are based on realistic two- and three-nucleon interactions between individual nucleons.

Disclosing the tiny effect of charge radii in the isotope shifts of beryllium required a dedicated experimental approach, because the voltage measurements of Doppler shifts are not sufficiently accurate. The problem can be circumvented by precisely measuring resonance frequencies ν_c for a collinear and ν_α for an anti-collinear laser beam applied simultaneously. Relativistic formulas then yield the rest-frame atomic transition frequency $\nu_0 = \sqrt{\nu_c \nu_\alpha}$. In this way the absolute transition frequencies as well as the isotope shifts for ^{7}Be to ^{12}Be were measured to about 0.1 MHz [10]. The determination of radii changes from the total isotope shifts then depends on accurate mass shift calculations for the atomic 3-electron system of Be+ [11].

The results of Figure 3 show decreasing charge radii from ^{7}Be to ^{10}Be and a marked increase towards ^{11}Be [10] and ^{12}Be [12]. The observed trends are well reproduced by several advanced theoretical models. The results from "Fermionic Molecular Dynamics (FMD)" calculations even provide a descriptive explanation of the effects seen in the radii and illustrated in the lower part of the figure. The essence is a cluster structure with ^{7}Be built of ^{3}He and ^{4}He (α particle), and the remaining isotopes of two α particles and additional neutrons. While two α particles (corresponding to ^{8}Be) do not form a bound system, additional neutrons act as glue which is stronger for ^{10}Be than for ^{9}Be. The increased charge radius for ^{11}Be is explained by the influence of a weakly bound halo neutron whose wave function extends far beyond the nuclear core [13], thus widening the proton distribution by the centre-of-mass motion. For ^{12}Be the further increase is related to a quenched N = 8 neutron shell effect.

We have shown how laser light has become an invaluable tool of nuclear structure physics. With newly developed atomic spectroscopy techniques it revived the traditional access to nuclear spins, moments and charge radii for wide ranges of nuclei, from heaviest to lightest and from stable to short-lived isotopes far from stability. ■

About the author

Rainer Neugart was teaching experimental physics at the University of Mainz. He introduced collinear laser spectroscopy at ISOLDE (CERN) and for many years he has carried out experiments exploring the properties and the structure of unstable nuclei.

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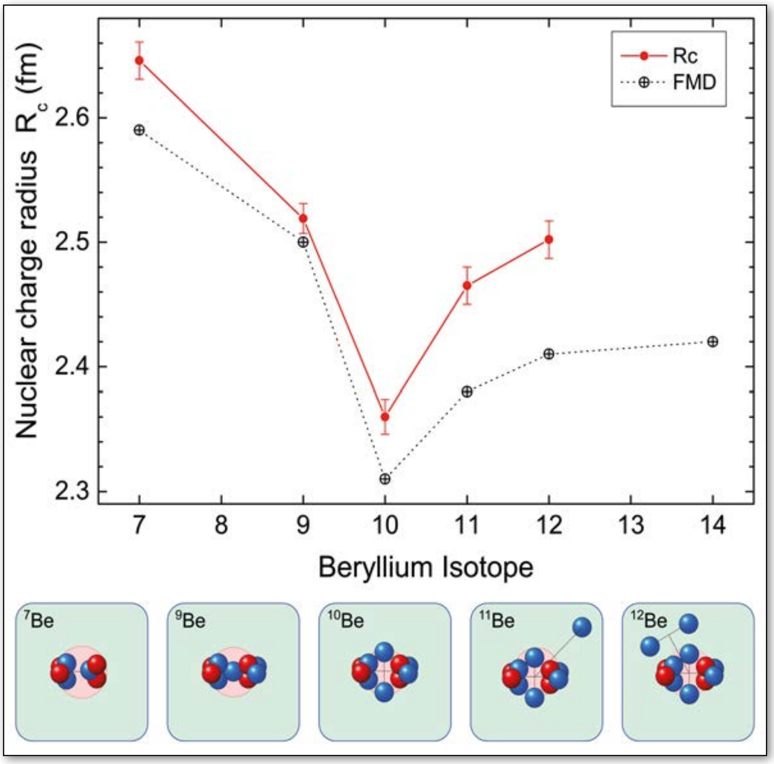
▾ **FIG. 3:** Beryllium nuclear charge radii and underlying cluster structure from FMD calculations. Protons are shown in red, neutrons in blue (Courtesy R. Sánchez).



by Herman C. W. Beijerinck
professor emeritus Eindhoven University of Technology – DOI: https://doi.org/10.1051/epn/2017202

Gender diversity in STEM

There is a strong business case for the value of diversity. Research by the World Economic Forum shows a 36% higher return on equity (ROE) for companies having a workforce with strong gender diversity[1]. Also growth is influenced in a positive way: in 2009 – 2012 companies with a strong female leadership have increased their ROE by 10.1% as compared to an average of 7.4% for the rest. Diversity is not a problem but a solution![2]

Why does it take us so long to achieve this goal? It is a complex problem requiring a broad approach to find the right knobs for tuning. Family life at home is the first hurdle to take. Both father and mother have a strong influence on interest in STEM subjects. Culture in society is a second hurdle. Role models are important. Gender equality does not exist: diversity is such a strong driver by the sake of differences. Gender differences are deeply rooted in the evolution of mankind. Mankind has to strive to create *equal opportunities* without loosing on *gender differences*. We as physicists should take our responsibility wherever we can.

There is evidence that (gendered) phrasing of job ads plays an important role in losing female applicants even before the selection process begins[3,4]. This is a subliminal effect that we are not aware of. For STEM jobs masculine phrasing is a pitfall. Nouns are at the masculine end of the spectrum versus adjectives at the feminine side. The WISE network in the UK has tested this aspect[3], showing a strong correlation between phrasing and response by women. Words such as competent, merit, potential, and gravitas are fatal for women. Men are less sensitive to gendered phrasing.

Diversity has many more aspects than only gender diversity. Physics diversity is also lacking in sexual orientation (LBGT), diversity in cultural background (BAME), and acquired or birth disabilities: Stephen Hawking is exception rather than rule.

Creating and maintaining diversity in science in general and STEM in particular requires a lifespan approach. Family, education, outreach programs of (science) museums[5] and libraries, career management in industry and academia, no step can be neglected to achieve this goal. Most important, however, is the mindset. Unconscious processes in our brain are at the root of making decisions. The right half decides and the left half makes up a nice story to support what already has been decided on. Accepting this insight is half of the work that lies ahead of us.

Based on the current annual growth in female engagement in STEM, the World Economic Forum predicts that it will take 170 years to achieve equal opportunities 1). Let us beat the current trend and do better than that. We always feel superior: let us act better than expected by looking in the mirror and accepting change. The VII Forum on Physics and Society meeting in London (2016)[6] can inspire EPS to make this effort. ■

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ION COULOMB CRYSTALS: FROM QUANTUM TECHNOLOGY TO CHEMISTRY CLOSE TO THE ABSOLUTE ZERO POINT

O. Dulieu[1] and S. Willitsch[2] – DOI: https://doi.org/10.1051/epn/2017203

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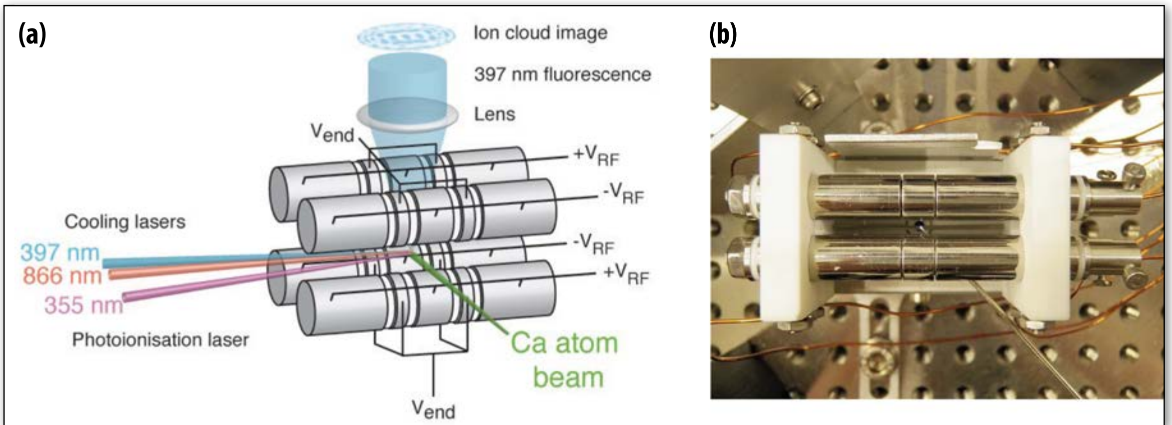
Ion Coulomb crystals are ordered structures of atomic or molecular ions stored in ion traps at temperatures close to the absolute zero point. These unusual "crystals" form the basis of extremely accurate clocks, provide an environment for precise studies of chemical reactions and enable advanced implementations of the technology for a quantum computer. In this article, we discuss the techniques for generating atomic and molecular Coulomb crystals and highlight some of their applications.

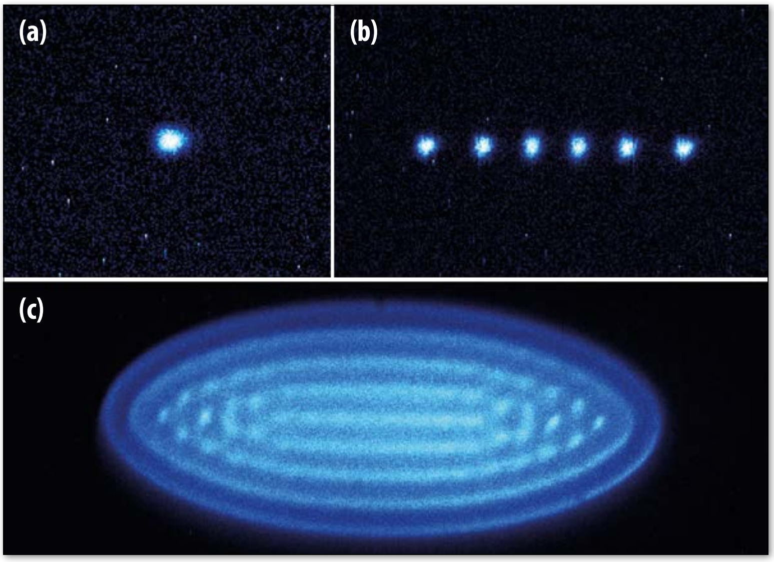
The recent progress in the generation of atoms and molecules at temperatures near the absolute zero point has paved the way for new exciting research directions in both physics and chemistry. A particularly intriguing form of cold matter is a "Coulomb crystal", an ordered structure of charged atoms or molecules (ions) stored in traps [1]. In such a crystal, it is possible to observe, address and manipulate single particles. This remarkable technology paves the way for a range of new applications. These include quantum logic and quantum simulation as new avenues for information processing, extremely precise atomic clocks as new time standards, precision spectroscopic measurements to address fundamental physical questions such as a possible time variation of fundamental constants, and controlled collision studies to unravel the fine details of chemical reaction mechanisms. The spectacular advances in this field have recently been recognized by the award of part of the Nobel Prize in Physics 2012 to David J. Wineland, one of its pioneers.

Generation of Coulomb crystals

There are two basic steps for producing a Coulomb crystal: the trapping of ions and their cooling. Trapping the ions is necessary because they strongly repel one another through their charge. A tightly packed cloud of ions would therefore immediately explode if it is not held together by external forces. The traps typically used in Coulomb-crystal experiments are linear radiofrequency traps, *i.e.*, electrodynamic traps consisting of an arrangement of electrodes to which time-varying



◂ **FIG. 1:** **(a)** Schematic of a Coulomb-crystal experiment. Laser-coolable ions such as Ca^+ are produced by ionisation from a Ca beam and are trapped in a linear radiofrequency ion trap. Laser beams are inserted into the trap for ionisation and cooling. The fluorescence generated during laser cooling is collected by a lens and imaged onto a camera. Adapted from Ref. [3]. **(b)** Photograph of a linear radiofrequency ion trap.



▲ FIG. 2: False-color fluorescence images of Coulomb crystals of laser-cooled Ca^+ ions in a linear radiofrequency ion trap. (a) A single Ca^+ ion, (b) a string of ions, (c) a large crystal. Adapted from Ref. [1].

and static voltages are applied (see Figure 1) [1]. A less frequently used alternative are so-called Penning traps which rely on magnetic and static electric fields to trap the charged particles [2].

Cooling the ions is necessary because Coulomb crystallisation can only occur if the potential energy of the ions exceeds their kinetic energy by a factor of ≈ 170 [3]. For light particles such as atoms, this can only be achieved if the temperature of the ion cloud is reduced to a few thousands of a degree above the absolute zero point (for large particles such as dust, this can already be achieved at much higher temperatures). Such low temperatures can be attained by laser cooling the ions, *i.e.*, by reducing their velocity through the repeated absorption of photons from a laser beam. Laser cooling, however, is only applicable to ions with a particularly simple quantum structure which enables the repeated absorption and emission of photons on the same spectroscopic transition. Certain atomic ions, for instance the ions of alkaline earth atoms magnesium, calcium and barium, fall into this category.

Figure 2 shows false-color fluorescence images of different Coulomb crystals of calcium ions in a linear Paul trap. Coulomb crystals can appear as single localized ions (a), as strings of ions (b) or as large crystals containing hundreds to thousands of particles (c). The images were recorded by collecting the fluorescence emitted by the ions during laser cooling and collecting them with a camera coupled to a microscope. Because of the finite depth of focus of the microscope, the images show a cut through the crystals along their central plane. The distance between the ions in the crystals typically amounts to a few tens of micrometres. Thus, big crystals such as the one shown in Figure 2(c) are macroscopic objects with sizes close to millimetres.

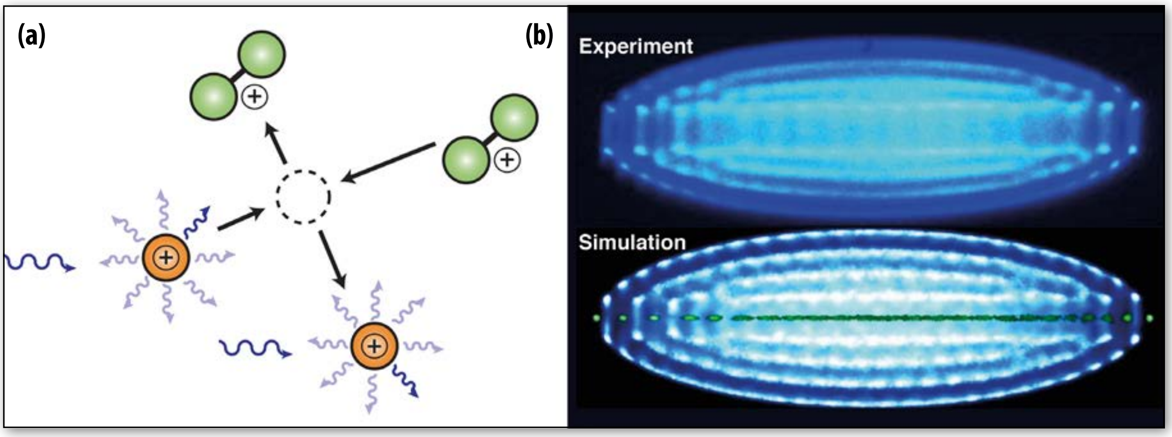
Large crystals have a spheroidal shape because of the harmonic trapping potential. In fact, the term "crystal" is a misnomer in this case because Coulomb crystals in harmonic traps do not have translational symmetry as required of a true crystal. Historically, the term originated in analogy to "Wigner crystals", ordered structures of electrons in solids originally predicted by the Hungarian-American physicist Eugene Wigner.

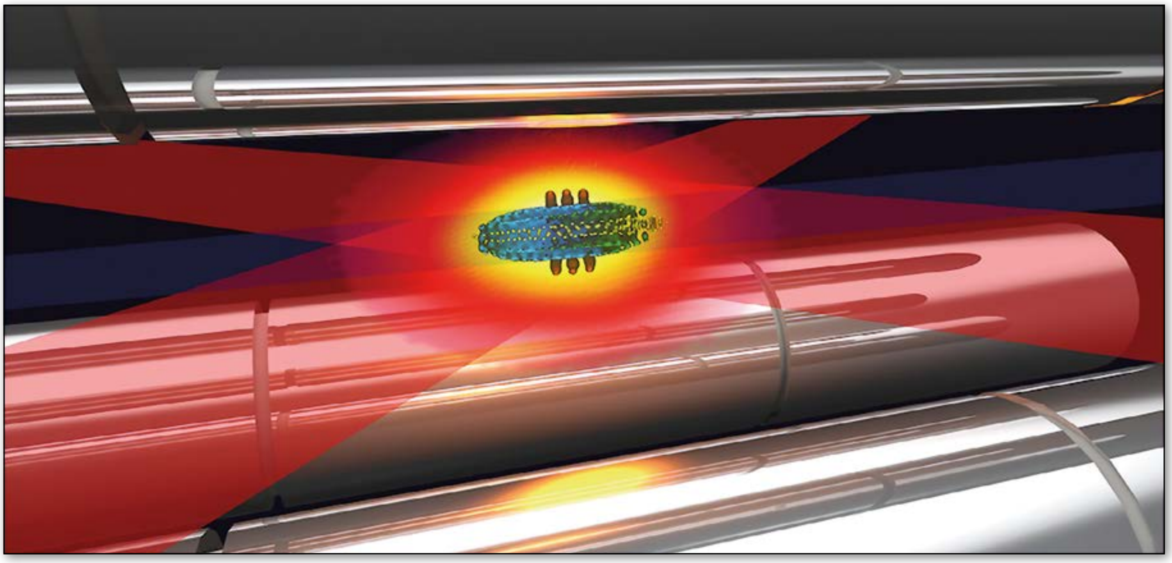
Coulomb-crystallizing molecules

In contrast to atoms, molecules can – with a few notable exceptions – not be laser cooled because of their complex energy-level structure. For molecular ions, however, a versatile and efficient method has been developed which allows their cooling to similar temperatures as laser-cooled atomic ions. The principle of "sympathetic cooling" is shown in Figure 3(a). Molecular ions are stored together with laser-cooled atomic ions in the same trap. Through collisions, the two species exchange kinetic energy which is ultimately removed from the atomic ions by laser cooling. As a result, a bi-component or "molecular" Coulomb crystal is obtained (Figure 3(b)) in which the molecular ions (nitrogen ions in this case) are embedded in the atomic Coulomb crystal. The molecular ions are not directly visible in the images in which only the fluorescence from the laser-cooled atomic ions is displayed, but they can be made visible artificially in molecular-dynamics simulations of the cold ions (shown in green in the bottom panel of Figure 3(b)).

One of the chief advantages of Coulomb crystals is the high degree of control which can be achieved over the trapped particles. While cooling freezes their motion and

▶ FIG. 3: (a) Molecular ions (green) can be sympathetically cooled by collisions with simultaneously trapped laser-cooled atomic ions (orange) leading to the formation of bi-component or molecular Coulomb crystals. (b) Top: Experimental image of a bi-component Coulomb crystal containing 25 sympathetically cooled N_2^+ ions embedded into ≈ 925 laser-cooled Ca^+ ions. The molecular ions are visible as a non-fluorescing region in the center of the crystal. Bottom: Molecular dynamics simulation of the crystal in which the molecular ions have been made visible in green. Adapted from Ref. [1].





◂ FIG. 4: Illustration of a Coulomb crystal of Ba^+ ions embedded in a cloud of ultracold Rb atoms held in a magnetooptical trap. Cold chemical reactions with the Rb atoms lead to a gradual replacement of the Ba^+ ions in the crystal (blue, green) with product ions (yellow, red).

fixes them in space, their internal quantum state can be manipulated by laser fields. This is fairly straightforward for atoms which only have electronic and nuclear-spin internal degrees of freedom. Achieving full quantum control over molecules, however, is much more challenging as they have additional internal degrees of freedom such as vibrations and rotations. Developing methods for the preparation and manipulation of the internal quantum state of Coulomb crystallised molecular ions has been a major objective of the field over the last years and has only been achieved recently [1].

Applications: From quantum logic ...

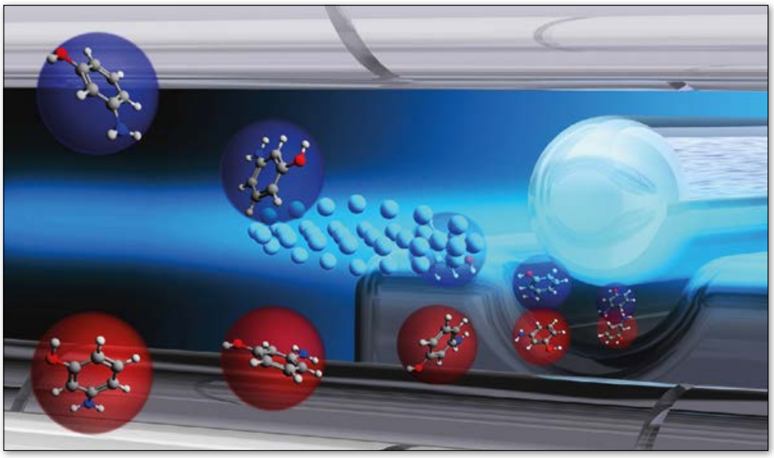
Trapped ions were the first particles in which laser cooling was demonstrated in the 1970s [4]. The scientific breakthrough of cold ions, however, only came in the mid-1990s when Ignacio Cirac and Peter Zoller realized that strings of Coulomb-crystallized ions could form a suitable basis for a quantum computer [5]. Indeed, ion-trap quantum information processing has become a thriving field on its own and experiments relying on Coulomb-crystallized ions count among the most advanced implementations of quantum-information processors to date [6]. Besides conventional quantum-information processing, quantum simulation, *i.e.*, the simulation of the dynamics of a particular Hamiltonian implemented in another system, has become another important application of Coulomb-crystallized ions.

... and precision measurements ...

The possibility to isolate single particles in the well-controlled ultrahigh-vacuum environment of an ion trap and to control their motion and internal quantum state has enabled the development of a new generation of ultra-precise atomic clocks which count among the most precise time standards to date [7]. These clocks rely on the measurement of electronic transition frequencies in a single trapped atomic ion. As these atomic transitions typically lie in the visible or ultraviolet region of the electromagnetic spectrum, the accuracy of these clocks far surpasses the one of conventional atomic clocks which relies on the measurement of hyperfine transitions in the radiofrequency domain. Besides providing an extremely accurate frequency (and thereby time) standard, such high-precision spectroscopic measurements also allow one to study fundamental physical problems which thus far have largely been the domain of particle- and astro-physics. These include the question of a possible time variation of fundamental physical constants such as the fine structure constant or the masses of fundamental particles [8]. Another impressive application of these highly precise frequency measurements is the study of the influence of gravitation on atomic transition frequencies [9]. Besides the atomic systems, cold molecular ions have recently also received considerable attention as potential candidates for new, highly precise clocks [10].

.... to cold and controlled chemistry

While the examples discussed thus far belong to the realm of atomic and quantum physics, the development of sympathetic cooling of molecular ions has also made chemists aware of the potential of Coulomb crystals. For instance, Coulomb-crystallised ions are ideal systems to study ion-neutral interactions and chemical reactions at extremely low temperatures. To this end, a range of different experiments has been developed over the past few years which combine ion traps with sources of either cold neutral atoms [11, 12] or cold neutral molecules [13]. Figure 4 shows an illustration of an experiment in which a Coulomb crystal of laser-cooled Ba^+ ions has been overlapped with a cloud of ultracold Rb atoms prepared by laser cooling and magneto-optical trapping [12]. Experiments like this allow the study of exotic chemical processes occurring at extremely low temperatures in dilute environments, *e.g.*, the formation of molecular ions by photon emission during collisions of the cold atomic ions with the cold neutral



▲FIG. 5: Illustration of a "controlled chemistry" experiment in which two different shapes (highlighted in red and blue) of the organic molecule 3-aminophenol were spatially separated through their interaction with an inhomogeneous electric field and directed at a spatially localised reaction target consisting of a Coulomb crystal of cold ions [14]. Experiments like this enables one to study in detail the influence of the shape of a molecule on its chemical reactivity. Illustration by Y.-P. Chang, DESY.

atoms. Besides the artificial environment created in these experiments, this sort of processes plays an important role in the chemistry of interstellar space. Combined cold-ion-neutral experiments also enable to unravel the detailed dynamics of collisions between three bodies, which are particularly important in dense media like Bose-Einstein condensates [11], and to explore subtle intermolecular interactions which manifest themselves at very low temperatures, but are often obscured at higher temperatures [12]. In this way, they enable a better understanding of the forces that drive chemical processes.

The intriguing properties of Coulomb-crystallised ions have recently also been used in the context of studying the mechanisms of reactions of complex molecules in unprecedented detail [14]. Large molecules can frequently assume different shapes, so-called conformations, which differ only by a rotation of parts of the molecule about a chemical bond. The influence of the specific shape of a molecule on its chemical reactivity is one of the long-standing problems in chemistry, but has been difficult to address experimentally so far because different conformations tend to interconvert into one another through their thermal motion. In a recent study, a mixture of two distinct molecular conformations of the organic molecule 3-aminophenole was entrained in a molecular beam in which their interconversion was suppressed through adiabatic cooling. Because the two different conformations of the molecule possess different electric dipole moments, they could be spatially separated through the interaction with a strong inhomogeneous electric field. This corresponds to an electrostatic, molecular version of the celebrated Stern-Gerlach experiment in which in 1922 the intrinsic angular momentum of electrons, the spin, was first observed experimentally through magnetic deflection. The spatially separated conformers were then directed at a stationary reaction target consisting of a Coulomb crystal of laser-cooled Ca^+ ions (Figure 5). In this way, the distinct chemical reactivities of the two molecular conformations could be characterised individually, shedding new light on shape-specific intermolecular interactions in chemical reactions.

Outlook

The past years have seen impressive progress in the development of the technology of Coulomb-crystallised atomic and molecular ions leading to the emergence of a new scientific field at the interface between quantum science, atomic and molecular physics and chemistry. Exciting future perspectives involve improved atomic clocks which will push the accuracy of frequency measurement to ever further limits, the development of quantum technologies for single molecules which augment and enhance the present capabilities with atoms, and new technologies to precisely study and control chemical reactions. Thus, one could say without exaggerating that cold ions have become a hot topic indeed! ■

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NATURE'S ENGINES: ACTIVE MATTER

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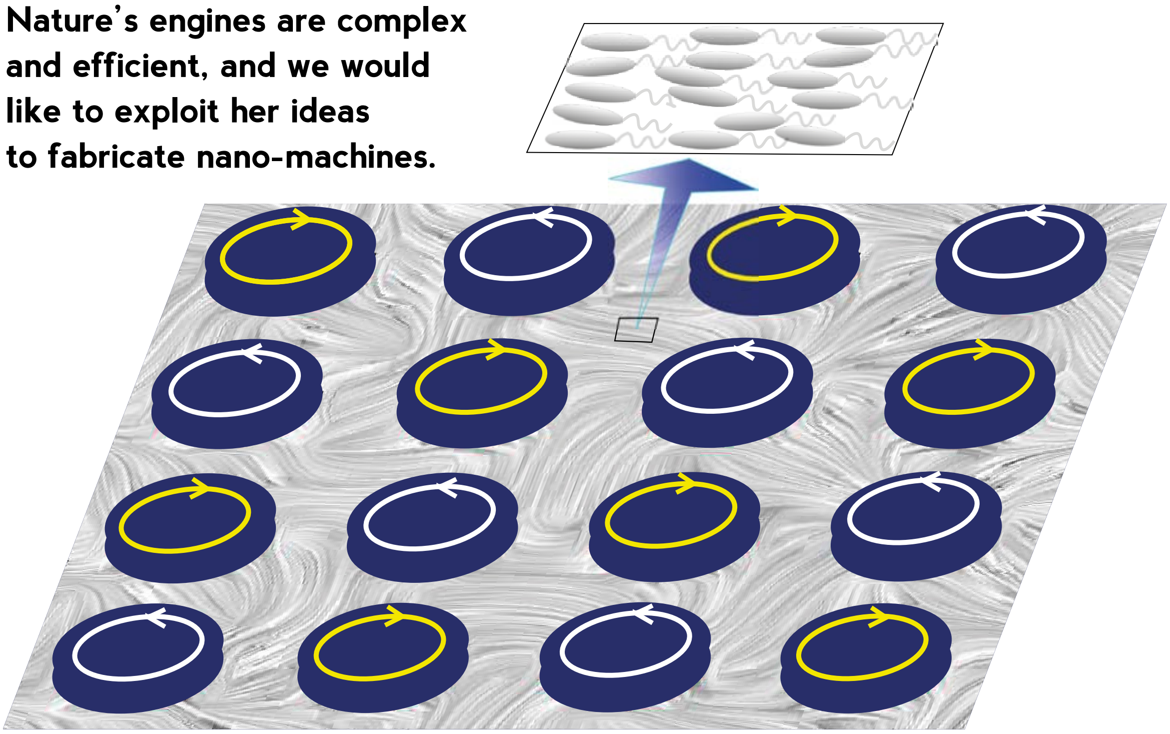
Active materials, bacteria, molecular motors, and self-propelled colloids, continuously transform chemical energy from the environment to mechanical work. Dense active matter, from layers of cells to flocks of birds, self-assembles into intricate patterns. Nature's engines are complex and efficient, and we would like to exploit her ideas to fabricate nano-machines.

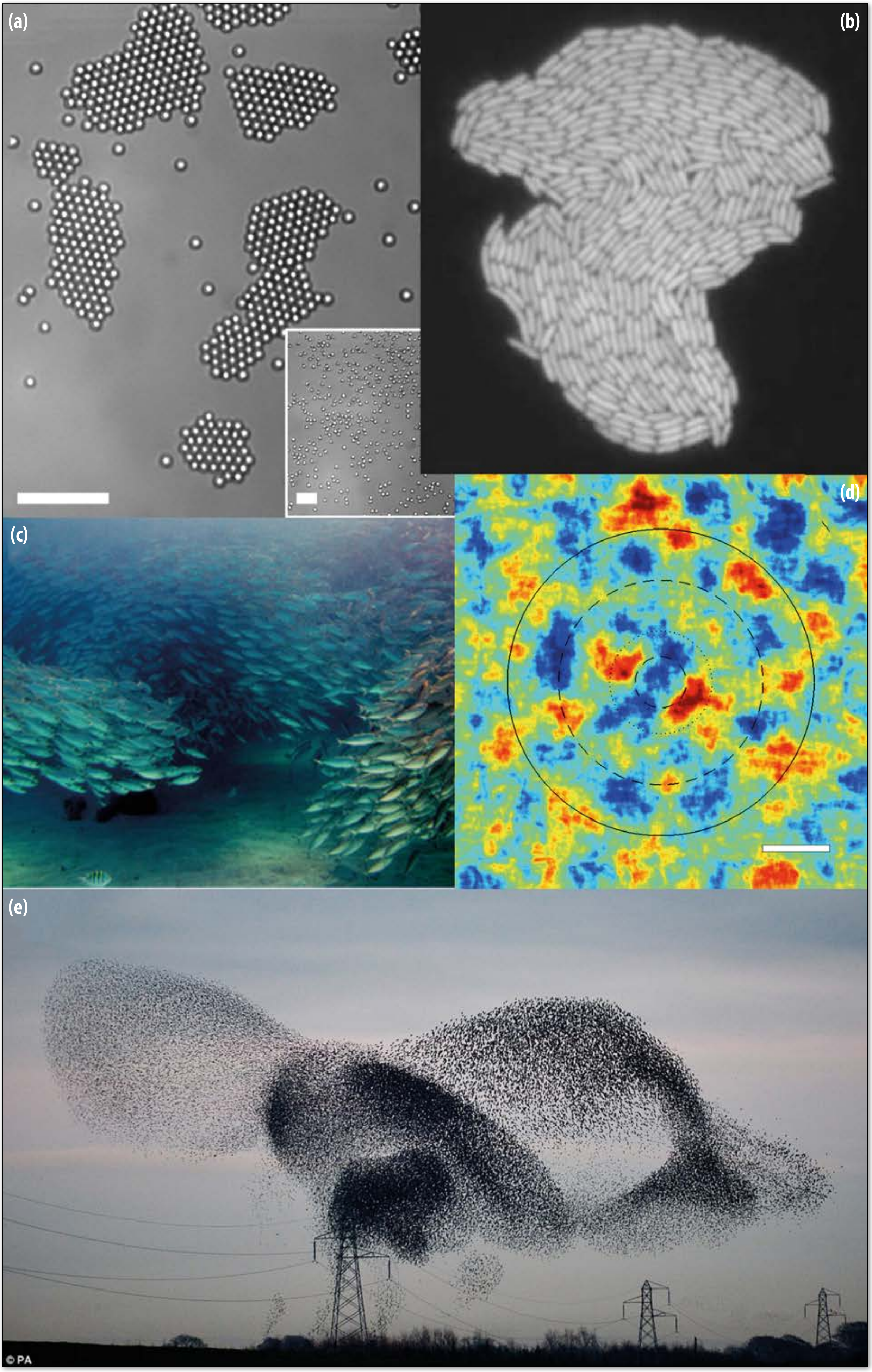


Active particles operate out of thermodynamic equilibrium. They take energy from their environment and use it to move or to do work [1,2]. Familiar biological examples are swimming bacteria and crawling cells. Perhaps less familiar are the motor proteins, for example myosin and kinesin, which are the engines of the cell (Box 1). Moreover many inanimate active systems can now be engineered.

These are often colloids, which can be driven by light and by local concentration gradients. Active matter is of interest to physicists because it is meant to exist out of thermodynamic equilibrium. Therefore it provides a platform for motivating and testing theories of non-equilibrium statistical physics. Moreover active systems have evolved to be very efficient tiny engines. Understanding how they self assemble and then operate may suggest novel energy technologies.

What happens to all the energy when active particles move together? A common behaviour is clustering. Dilute colloids undergo Brownian motion and do not order. However when they become active, so that there is a ballistic as well as a Brownian component to their velocity, they aggregate in dynamic groups (Fig. 1a). This can be partially explained by theories that assume that the active particles' velocity depends on their density [3]. Flocking, exemplified by the beautiful swirling patterns of starling flocks coming in to roost, is another collective behaviour characteristic of active systems; one that is still not well understood (Fig. 1e).

Bacteria are a few microns in length and the Reynolds number governing their flow is tiny, typically ~10^{-4}. This is far into the viscous regime where flows are expected to be linear and time reversible, and mixing difficult. Therefore it was a surprise when Dombrowski *et al.* showed that in a dense, two-dimensional layer of bacteria the velocity field of the cells appears turbulent [4]. Flow vortices, swirls and jets form on length scales ~5-10 times that of an individual bacterium (Fig. 2a,b).



▶ FIG. 1: Active matter: **(a)** Colloids, activated by light, cluster when the light is on but disperse when it is turned off (bottom right), after [13]; **(b)** growing E-coli colony; **(c)** fish shoaling; **(d)** flow field around a dividing epithelial cell, the colours represent vorticity: clockwise (blue) and anticlockwise (red), after [14]; **(e)** starlings flocking.

Active turbulence has now been observed in active systems over a range of length scales [5]. An example is a suspension of microtubules and two headed, kinesin motor proteins (Box 1). The molecular motors bridge pairs of microtubules, holding them together to form microtubule bundles. These motors are directed; they move in a particular sense along their tracks. This means that motors bridging oppositely aligned pairs of microtubules will push them past each other as they walk, extending the filament bundles. The bundles then buckle and drive turbulent flows. Dense layers of cells, for example epithelial cells that line body cavities and organ surfaces, are also active. The activity is due to both cell motion and cell division. There is increasing evidence that these confluent cell layers can also show the vorticity which characterises active turbulence (Fig. 1c).

Active turbulence shares similarities across the diverse systems and length scales, most obviously the highly vortical and unsteady nature of the flow. Details remain to be worked out, but we understand why active turbulence occurs. The reason can be traced right back to Newton's laws of motion. Active particles swim by exerting forces on the surrounding fluid. They are moving autonomously, with no external driving, and therefore at any time forces or torques must be balanced in equal and opposite pairs. Fig. 3c shows that the same is true for the kinesin motors: they exert equal and opposite forces on neighbouring microtubules. Such force dipoles have nematic (head-tail) symmetry which is well known in liquid crystals (Box 2). Therefore the far flow field produced by the microswimmers or motors also has nematic symmetry.

The symmetry properties of the active flow mean that passive liquid crystals in the nematic state provide a useful starting point to understand dense active systems, which are often termed active nematics. In particular, continuum equations of motion rely primarily on symmetry. Therefore the equations describing how active nematics flow are very similar to those for passive nematic liquid crystals. Just one addition is needed to introduce the activity; an extra term in the stress tensor. Because the active term contributes to the stress it appears under a derivative. This implies that any changes in the direction or magnitude of the nematic order contribute to stresses that drive flows.

An important consequence of this extra, active stress term is that it destroys the nematic ordering [6]. Any small fluctuations from perfect nematic alignment cause shear flows that enhance the fluctuations. This drives the ordered nematic state unstable, which results in active turbulence. Fig. 2c shows simulations of the nematic director field (the swimmer or microtubule directions) in the active turbulent state. The nematic ordering is strongly deformed and the resulting stresses drive the turbulent-like velocity field characterised by flow jets and flow vortices.

Topological defects are a defining feature of passive liquid crystals (Box 2). They lead to distinctive and beautiful images if liquid crystals are placed between crossed polarisers, but are usually a nuisance in applications, reducing the efficiency of liquid crystal displays. Topological defects are energetically unfavourable and anneal out in passive nematics. In active systems, however, they make an important contribution to the energy balance.

In regions of high nematic distortion, the elastic energy and the active flow are able to overcome the energy barrier to creating pairs of topological defects. The defect pairs can escape their mutual attraction because they are mobile: the distortions in the nematic field around a defect drive

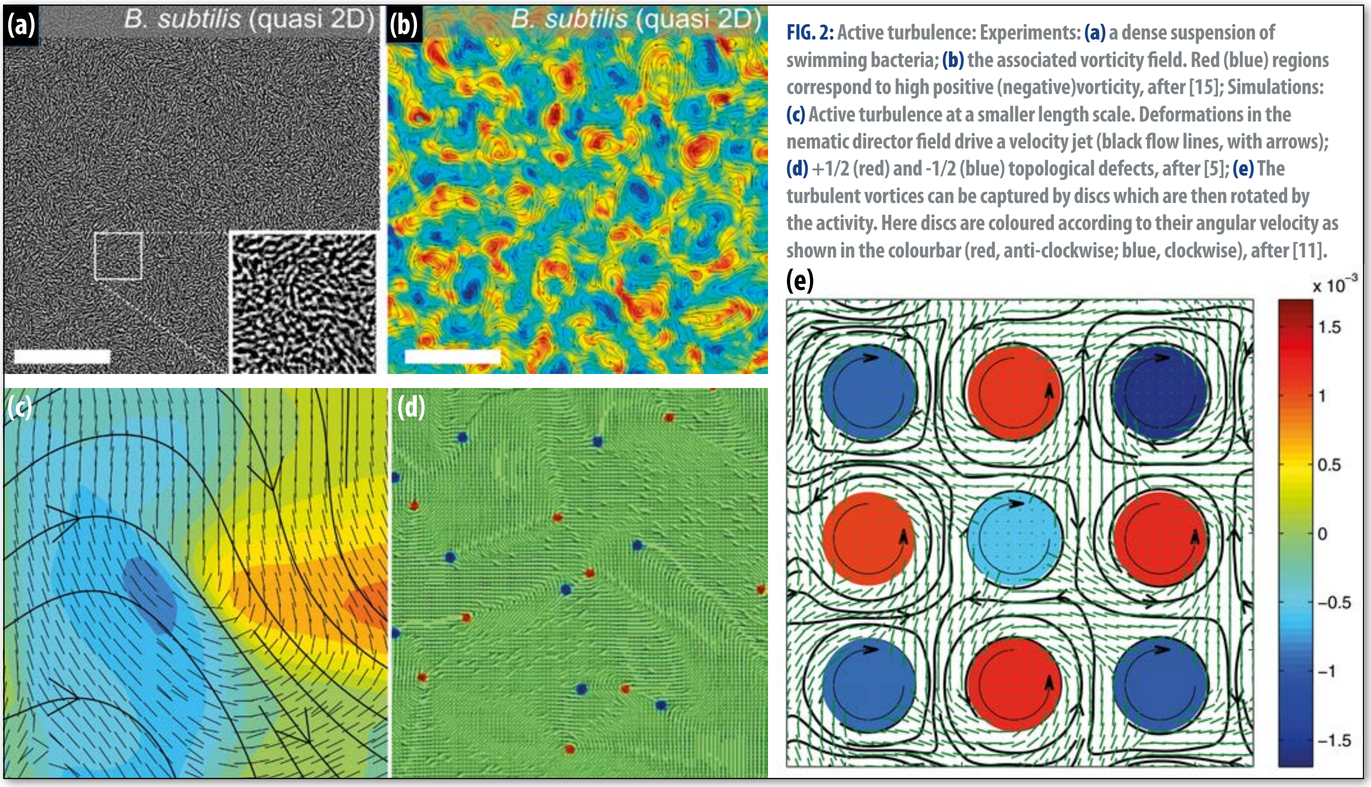


FIG. 2: Active turbulence: Experiments: **(a)** a dense suspension of swimming bacteria; **(b)** the associated vorticity field. Red (blue) regions correspond to high positive (negative)vorticity, after [15]; Simulations: **(c)** Active turbulence at a smaller length scale. Deformations in the nematic director field drive a velocity jet (black flow lines, with arrows); **(d)** +1/2 (red) and -1/2 (blue) topological defects, after [5]; **(e)** The turbulent vortices can be captured by discs which are then rotated by the activity. Here discs are coloured according to their angular velocity as shown in the colourbar (red, anti-clockwise; blue, clockwise), after [11].

flows. For a +1/2, comet-like, defect these are unbalanced and the defect moves away from its -1/2 twin until it meets a different -1/2 defect and annihilates with it. Thus, in the steady state, topological defects are created in pairs, unbind, and annihilate in (generally) different pairs. As they move apart they restore regions of nematic order. These are again unstable to shear flows set up by fluctuations, and the dynamic steady state of active turbulence is established.

Fig. 4c shows a pair of defects forming and moving apart in a microtubule - molecular motor suspension. An observation, which is still lacking an explanation, is that for thin active layers the +1/2 topological defects are themselves aligned nematically: the vectors joining the comet head and tail are predominantly parallel or antiparallel [7].

Nature's engines, bacteria, cells and molecular motors, are miracles of engineering. Understanding and mimicking their design principles is becoming a feasible scientific endeavour. To compare: the motor that turns the bacterial flagellum is about 35 nm in diameter and is made up of a complex self-assembled array of proteins. It uses a proton current across the cell membrane to turn a flagellum of length ~10 µm at up to 1,000 rpm. Examples of state-of-the-art, man-made nanomotors are magnetic helices of width 100 nm and length 400 nm, driven by a magnetic field at similar frequencies [8].

Very recently ways have been proposed to harness the energy in active turbulence [9,10,11]. If bacteria are confined to a channel or circular well, which is about the same size as the velocity vortices, the turbulence is replaced by steady flow which could be used to drive micro-propellers. Turbulence in the microtubule - kinesin systems can be controlled by putting a layer of the active fluid next to a passive liquid crystal. Ordering in the passive liquid crystal exerts an anisotropic frictional force on the active suspension and this constrains it to flow in a preferred direction. Simulations have shown that active matter can be used to drive arrays of microscopic gears (Fig. 2e) – the bacterial wind-farms of the future perhaps? ■

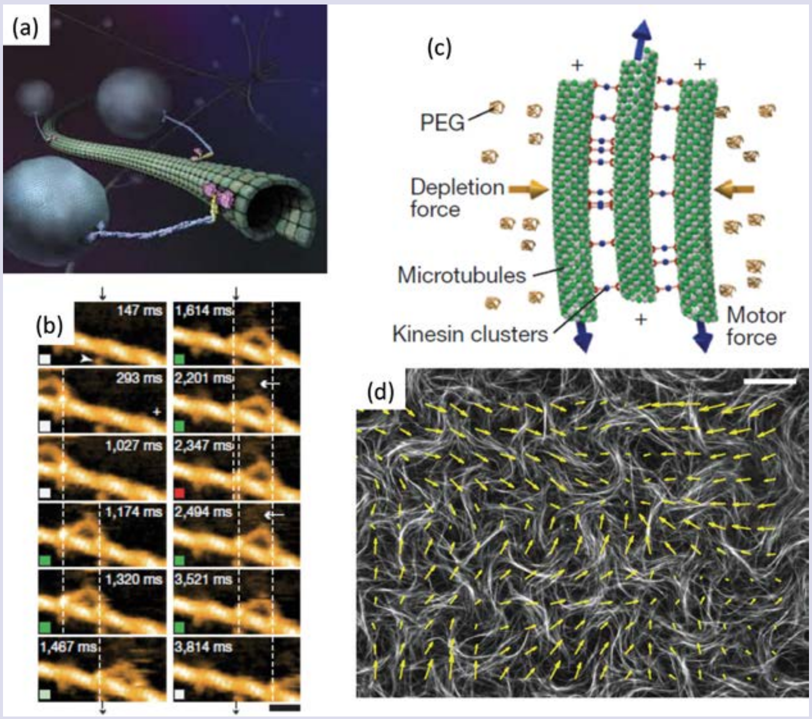
About the Author

Julia Mary Yeomans FRS is Professor of Physics at the University of Oxford. Among her current research interests are microswimmers, active systems, liquid crystals and the interactions of fluids with structured surfaces.

BOX 1: MOTOR PROTEINS

Animals like machines need engines. Molecular motors, for example myosin and kinesin, are the engines of the cell. They are responsible for mechanical biological processes as diverse as muscle contraction, turning the bacterial flagellum, cell crawling, transcribing RNA from DNA and moving large molecules around.

The motors proteins are tens of nanometres in size, yet have to operate in the strongly fluctuating crowded cellular environment. To cope with moving in a microscopic gale, motor proteins responsible for intra-cellular transport, such as kinesin, are attached to microtubules, long polymers of tubulin. The tubulin can self-assemble and disassemble as required, creating an evolving network of railway tracks. The motors move along the microtubule tracks in a gait that resembles walking. The back head unbinds, driven by ATP, and tends to move past the front head and reattach. These tiny motors drag around vesicles, membrane sacks, containing proteins and they are responsible for arranging chromosomes ready for cell division.



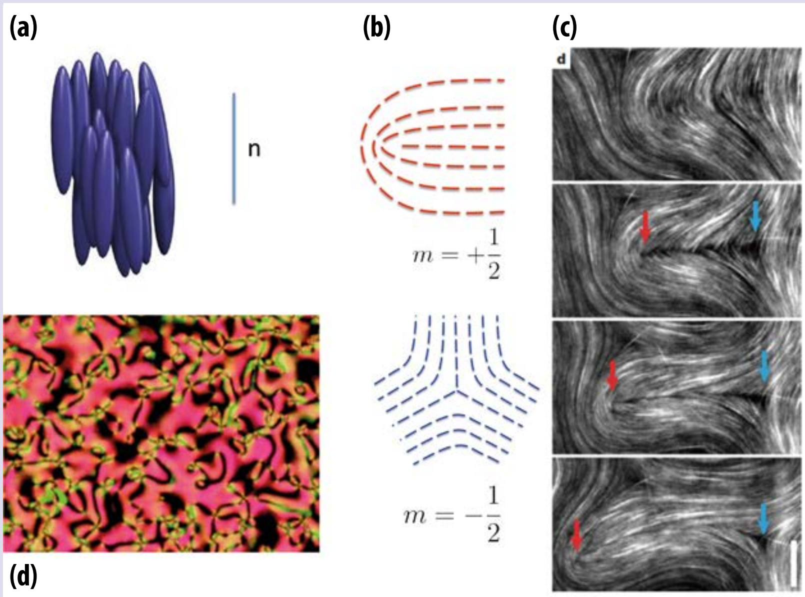
▸ **FIG. 3:** Motor proteins: **(a)** Graphical representation of kinesin motors walking along microtubules. See Youtube: Inner life of a cell for an animated version; **(b)** High speed atomic force microscopy images; successive snapshots show myosin heads moving along an actin filament, after [16]; **(c)** Microtubules bridged by two-headed kinesin motors; **(d)** microtubule bundles (white) driven by the motors. The yellow arrows show the velocity field, after [17].

BOX 2: NEMATIC LIQUID CRYSTALS AND TOPOLOGICAL DEFECTS

Long, thin molecules or colloids can form a nematic phase which is characterised by long-range orientational order (Fig. 4a) [12]. On average the rods point in the same direction, described by an order parameter called the director. The director is a 'headless' vector reflecting the head-tail symmetry of the nematic particles. The nematic is stabilised primarily by entropy as the rods have more room to move around if they lie parallel. Note that there is no long-range order in the rod positions, as would be the case in a crystal.

Nematic liquid crystals are elastic liquids. They flow, but also resist deformations that tend to destroy the alignment of the rods.

The nematic symmetry implies the possibility of topological defects, mistakes in the nematic ordering that cannot be corrected by local rearrangements of the director field. In two-dimensional nematics the most common topological defects, labelled m=+1/2 and m=-1/2, are shown in Fig. 4b. Single topological defects cannot exist in a perfect nematic as they have infinite energy. Defects pairs can form as a liquid crystal orders in the nematic state, between regions of different director orientation. +1/2 and -1/2 defects then attract each other, in a way similar to electric charges, and slowly anneal out.



◂ **FIG. 4:** Topological defects: **(a)** Nematic phase characterised by a director n indicating the average direction of the nematogens; **(b)** topological defects in the nematic field, characterised by topological charge m=+1/2 (red) and m=-1/2 (blue); **(c)** topological defects forming in an active suspension of microtubules and kinesin motors, after [17]; **(d)** a nematic liquid crystal between crossed polarisers: the pattern results from topological defects in the nematic ordering.

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A BRIEF TOUR OF THE CLIMATE MACHINE
1 - THE CLIMATE MACHINE, A TWO FLUIDS THERMAL ENGINE[1]

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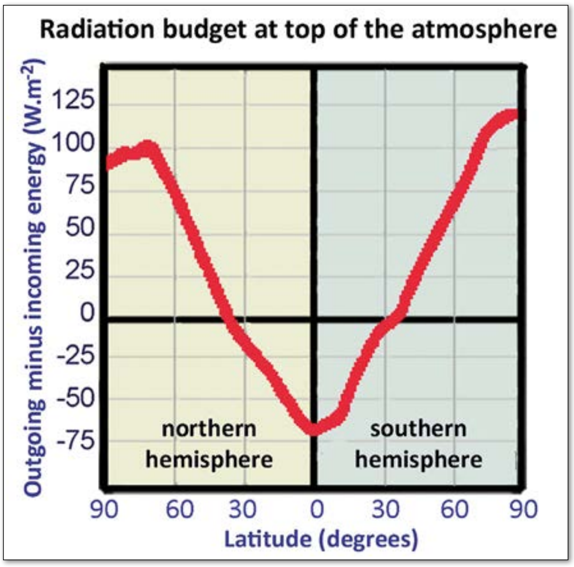
The climate machine is a thermal engine that gets all its heat from the sun and redistributes it on the Earth surface through coupled fluid circulation of the atmosphere and the ocean. Water present on Earth in its three physical states — solid, liquid and gas — plays a key role in the climate.

▼ Climate results primarily from the transport of solar energy by ocean and atmosphere.

Climate: this word usually applies to weather conditions such as temperature, rainfall and wind patterns. Historically, climatology first endeavoured to describe such conditions. Another way to define a climate is to refer to the biosphere which spontaneously develops: vegetation which has long been used to identify various climatic entities, but also fauna that prospers. Concurrently physical sciences have allowed to decrypt and then to model how the climate engine works [2]. Numerous processes in the external envelopes of Earth are interacting with each other. The aim of the present paper is to help the reader get acquainted with the two major actors and mechanisms creating the climate. The role of interactions with the environment will be presented in the next issue of EPN.

The climate machine is a thermal machine that gets its energy from the sun (the geothermal flux amounts to only 0.03% of the solar flux absorbed by the Earth).

The Earth (atmosphere and surface) reflects back to space 30% of the incoming sun energy; the remaining 70% is absorbed and transformed into heat. The excess heat is evacuated into space as electromagnetic radiation, the only form of energy that can propagate in the interstellar vacuum. Since the Earth is a sphere, the amount of energy that it receives from the sun is unequally distributed at the Globe surface, being highest at low latitudes.



◂ **FIG. 1:** Difference between the energy that escapes Earth and the incoming solar energy as a function of latitude (ERBE 1984–2003). Except around 30° N or S, the budget is not balanced. The equator sends back to space only a fraction of what it gets; it is the opposite at high latitudes.

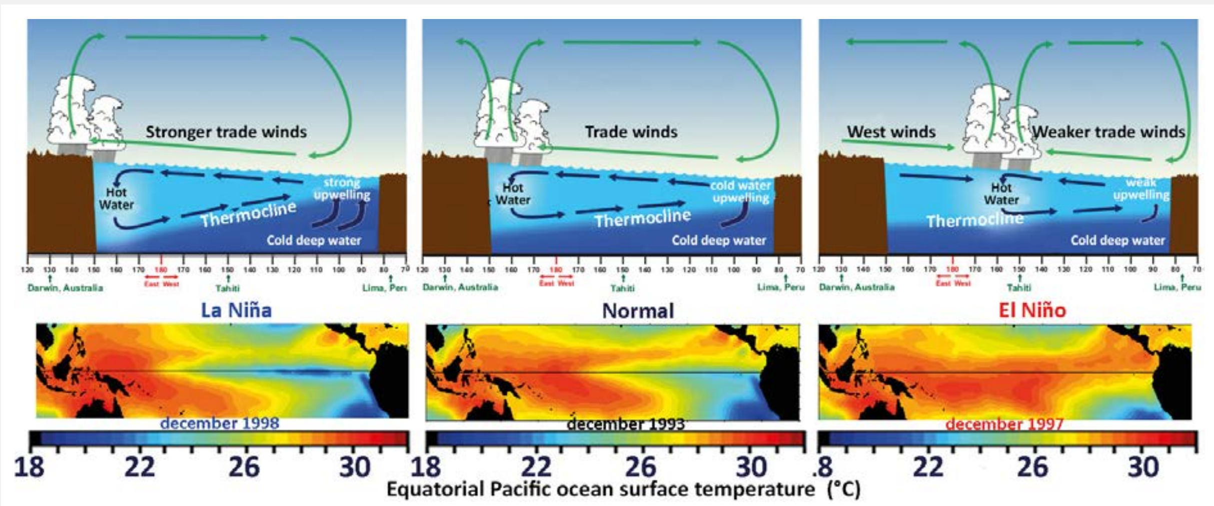
At any point, the average temperature would be stable if the amount of energy escaping Earth were equal to the amount of incoming solar energy. Satellite observations show that this radiation budget is positive (the incoming energy exceeds the escaping energy) in the tropics, and negative in polar regions (Figure 1). Thus, energy is transported from low latitudes to higher latitudes.

Both fluids of the Earth envelope contribute to this transport by roughly the same amount.

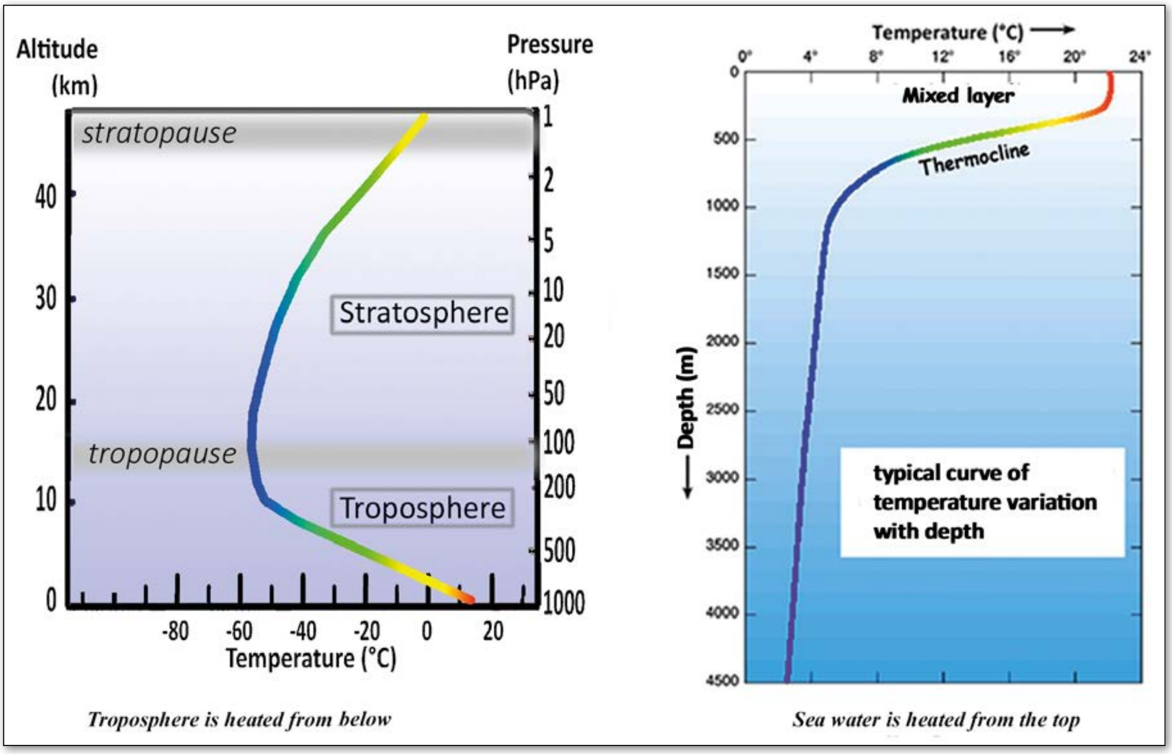
*Retired from LSCE.

BOX 1: EL NIÑO – LA NIÑA

In the equatorial Pacific ocean, high pressures are normally located on the eastern side, along Peru's coasts, and low pressures on its western side over the Philippines Islands. Every 3 to 7 years, trade winds weaken and warm water flows back eastwards. This El Niño event may produce severe rainfalls on Peru and a strong drought in the Philippines. Away from the intertropical Pacific, a strong El Niño affects also the Indian Ocean and eastwards, as far as the western edge of the Atlantic. An El Niño event is often followed by the reverse phenomenon La Niña, which is characterised by stronger trade winds and the shrinking of the warm pool.



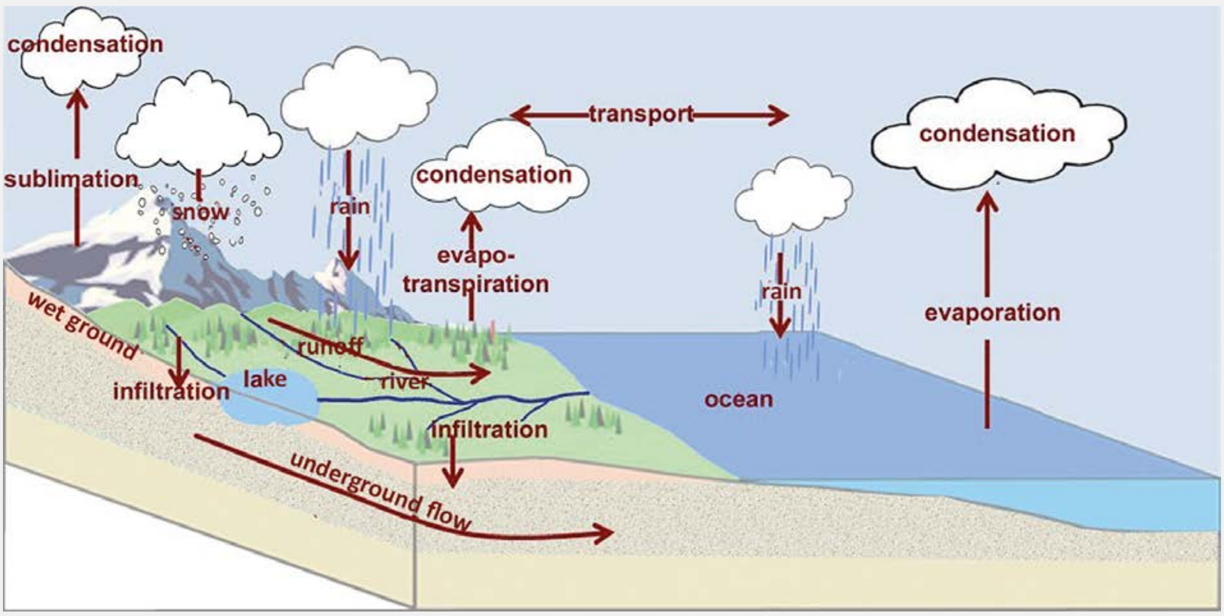
▴ The three states: La Niña, normal and El Niño, correspond to very different ocean and atmosphere patterns in the equatorial Pacific, with strong impacts on surface water temperatures.



▸ FIG. 2: Typical vertical temperature profile of the atmosphere (left) and of the ocean (right). The troposphere which contains most of the atmospheric mass in the first 10 km is heated from below while the ocean is heated from the top. (The temperature increases with altitude in the stratosphere due to UV radiation absorption by ozone).

BOX 2: WATER CYCLE

The Earth contains 1.4 billions km^3 of water: about 2.2% in ice mainly in the Antarctic, 95% in the ocean, 1% to 20% in underground waters, the remaining in lakes, rivers, inland seas, cells of living bodies, and only 0.001% in the atmosphere. Ocean evaporates 410,000 km^3 of water per year. Water vapour travels about 1000 km in 15 days in the atmosphere before condensing to build clouds where the water droplets and ice crystals grow by coalescence until their weight exceeds air resistance and they fall down. 110,000 km^3 of water falls on continents where 70,000 km^3 evaporate or sublimate either directly or through evapotranspiration from the vegetation and soil. The remaining 40,000 km^3, run off or infiltrate the ground before reaching oceans by rivers or by underground flow, or by melting of glaciers and icebergs (1,200 km^3 of water). Globally 370,000 km^3 of water come back to the ocean as rainfalls.



Heat transport

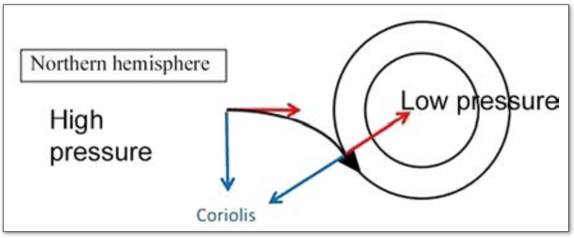
On continental surfaces, the solar radiation is absorbed by the soil; in the ocean, it is absorbed in the first metres below the surface. Heat is thus transmitted to the troposphere from below, while the ocean is heated from the top. Hence, the vertical temperature distribution is completely different between both fluids (Figure 2). Vertical transport is essentially driven by local fluid density. Within the atmosphere, the lifting of air warmer and thus less dense than the surrounding air, and the downwards motion of cold air, occur through convection loops. In the ocean, the density gradients are due to temperature and salinity; water is usually warmer at the sea surface than deeper. When ice forms at the surface of seawater, it rejects salt ions, so the surrounding seawater increases in density, causing it to dive to the sea bottom.

The vertical transport in the atmosphere generates pressure variations which drive horizontal air motion, *i.e.* winds. If the Earth were not rotating, the motion would simply be from high pressures to low pressures. The Coriolis force deflects the motion and thus winds move rightwards in the northern hemisphere, leftwards in the southern hemisphere, letting winds turn around lows (Buys-Ballot); this is called the geostrophic circulation (Figure 3). The global wind pattern is schematically shown in Figure 4.

Winds are altered by the topography and by the roughness of regions they pass through. At the sea-ocean interface, momentum exchange between the two fluids is the source of marine surface currents (down to about 1000 m depth). Due to the Coriolis force, these currents draw large loops in the great ocean basins, the gyres; the Gulf Stream is the western branch of such a gyre.

The world ocean is also crossed by a deep circulation called the thermohaline circulation, which is driven by density, *i.e.* by water temperature and salinity. Water on its way to the high polar latitudes loses heat transmitted to the atmosphere by infrared radiation, sensible heat and evaporation, the latter one making it saltier. Freezing sea water is very cold (-1.8°C). At the ice water interface, salt tends to migrate from solid to liquid phase, releasing brines that further increase water salinity. Being very dense, the water plunges down to the ocean bottom where it starts a long journey through the entire world ocean before it eventually goes up slowly into the surface currents which finally carry it back to its plunging point after a trip that may have lasted 1000 years. This long course is known as the ocean conveyor belt (Figure 5). Thus, the diving of water in the far north is the driving force of the North Atlantic Current that brings the warm water of the Gulf Stream to Europe.

Winds also drive cold water to rise to the surface (the upwellings) on the edges of continents and in the intertropical convergence zone.



◂ **FIG. 3:** The force caused by the pressure gradient (in red) is balanced by the Coriolis force (in blue). The wind follows the isobars (lines of constant pressure).

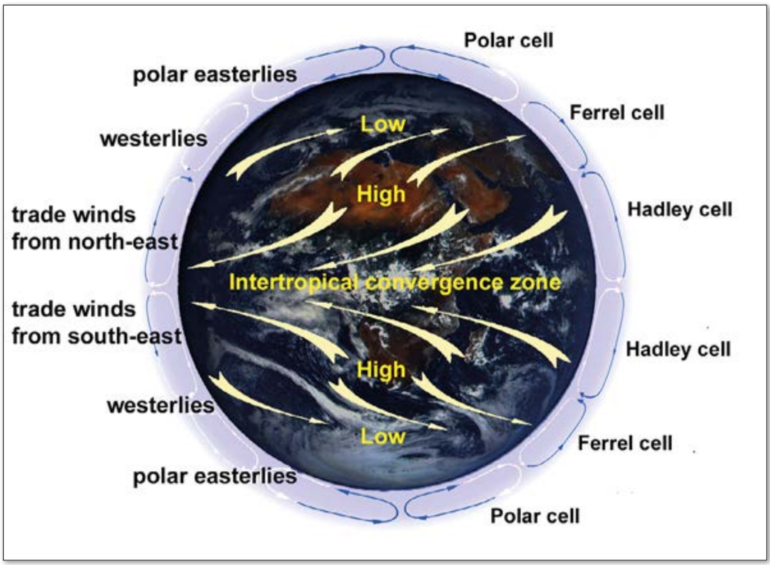
The climate mechanism involves in a tightly coupled way both fluids of the Earth's envelope. At their interface, they exchange heat (sensible and mainly latent), momentum (causing marine surface currents), liquid and gaseous water. The oceans also provide the atmosphere with mineral salt particles from sea-spray, and sulfur compounds (emitted by the plankton). These compounds will oxidise and form condensation nuclei necessary for the formation of clouds. Process times and sizes have very different values in the atmosphere, the surface and the deep ocean : few days in the atmosphere with coherent eddies that may span several thousands km, whereas they do not exceed some hundred km in the ocean but with reaction times ranging from months to millenia. This results in a complex coupled system subject to internal oscillations, the most widely known being the El Niño–La Niña Southern Oscillation (see box 1).

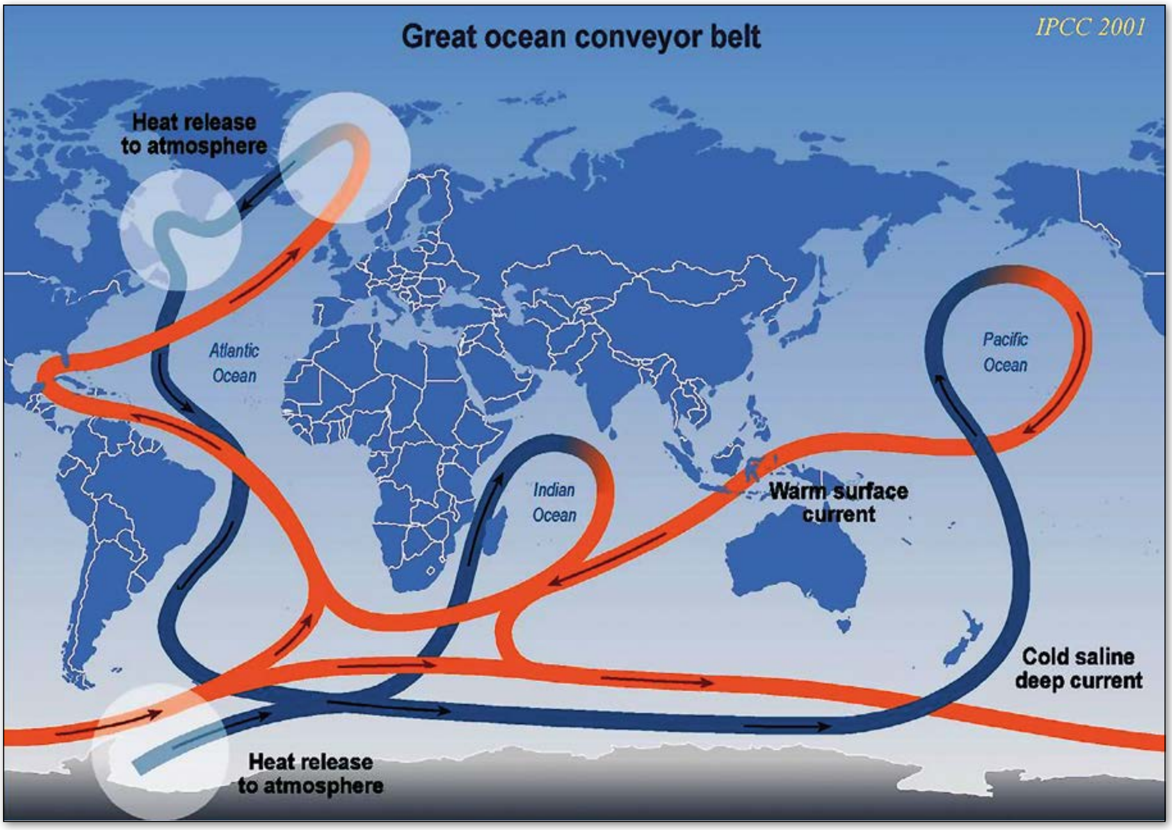
Water in all its states

All three water phases play an essential role in the energy budget and in the way that climate is operating (see box2).

- Evaporation which occurs mainly from the oceans, cools their surface since water vapour brings to the atmosphere its evaporation latent heat. This heat is carried away by the humid air masses and given back to the atmosphere at the condensation location after about 15 days on average. The heat thus delivered maintains deep convections that feed depressions. It acts in building large storm cumulonimbi. It gives their energy to tropical storms (hurricanes, cyclones, typhoons). The convection tied to vapour condensation with intense rainfalls in the intertropical

▾ **FIG. 4:** Schematic view of the global winds pattern. The polar cell is similar to the Hadley cell (described in the text below) with very dry air going down at the poles. The Ferrel cell results from interactions between hot air masses coming from the Hadley cell and cold air masses coming from the polar cell which generate successive lows and highs in the barometric pressure that are transported in Rossby waves [3]).



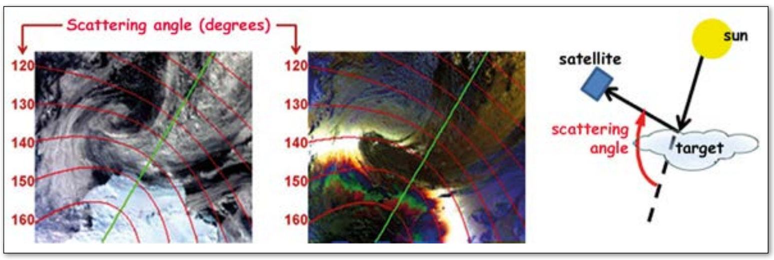


▸ FIG. 5: Thermohaline circulation (conveyor belt). In blue, deep cold water circulation; in red, warm water surface circulation. In the areas of deep water formation, the atmosphere gains heat from the ocean.

zone is responsible for the strong atmospheric ascend that generates the Hadley cell (Figure 4).

- Water vapour is mainly located in the lower troposphere. It accounts for 50% of the natural greenhouse effect. The amount of water that can stay in the atmosphere increases with temperature (Clausius-Clapeyron) by about 7% at customary temperatures.
- Low clouds are made up of liquid water (Figure 6). They screen incident solar radiation (parasol effect). High clouds (cirrus) are made up of ice crystals. They absorb infrared radiation and contribute to heat confinement in the lower troposphere.
- In its solid state water occurs in high clouds, in snow and hail falls, and in the cryosphere: sea ice, continental and alpine glaciers, permafrost, snow on the ground. Due to their very high reflecting efficiency (albedo, up to 90%), snow or ice covered areas limit strongly local absorption of solar radiation. The liquid-ice threshold (0°C for freshwater) is often crossed by water on the Globe surface. When this threshold is crossed, the huge change of albedo results in a non-linear behaviour of the climate: effects are much larger than the initial small change in temperature.

▾ FIG. 6: The same area over the Antarctic measured by the satellite radiometer POLDER in natural light (left) and in polarised light (right). Some of the water clouds seen in the left picture exhibit a rainbow pattern in polarised light. They are partly hidden by high altitude ice clouds which don't polarise light.



Conclusion

The processes occurring in the two fluid envelope of the Earth are only a part of the climate system. As will be shown in the second part of this tour in the climate machine, their various interactions with the Earth environment are essential in fashioning the climate. ■

About the Author

Jean Poitou. Physicist, climatologist. Former deputy director of LSCE. Active in climate related NGOs and in introducing climate science to secondary-school pupils.

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Le climat : la Terre et les hommes. Jean Poitou, Pascale Braconnot, Valérie Masson-Delmotte. Collection « Une introduction à », EDP Sciences (2015)

Le climat à découvert. Catherine Jeandel, Rémy Mosseri. CNRS Éditions (2011)

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[4] More about greenhouse effect in the second part of this tour of the climate machine, to be published in the next issue of *EuroPhysics News*.

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Travel with hydrogen

In the field of transportation, hydrogen does not have a particularly glorious history. Just think of the dozens of hydrogen airships destroyed by fire over the years, with the Hindenburg disaster in 1937 as the most famous example. Now H_2 is trying a comeback on the road, often in combination with a fuel cell and an electric motor to power the car.

The problem, of course, is that finding a compact and light-weight storage medium for hydrogen is not easy. The reason is the very nature of the H_2 molecule. Consisting of only two protons and two electrons, the intermolecular attractive forces are weak, which in turn makes the attractive potential well very shallow. The first consequence is that the boiling point is quite low: 20.4 K. Storing H_2 in liquid form therefore requires a cryogenic container. The second consequence is that it takes only little energy for the molecules to escape from the potential well: the heat of vaporization is quite low. So if you want to store liquid hydrogen in your car, the 'boil-off' is a serious problem; you don't want to return from a conference and find your fuel tank empty.

So, for application in automobiles a high-pressure tank seems to be the better option. But also here we face a slight drawback. Since the repulsive forces are far dominant at ambient temperatures, compression of the gas does not follow the ideal-gas law. For example, at 700 bar – which is the pressure in use nowadays – the density is only 2/3 of what one would expect naively.

How does this compare with storing energy in batteries? In contrast to H_2, where progress is frustrated by the nature of the molecule, in the case of batteries progress is determined by technology. And indeed, tremendous progress has been made, especially for Li-ion batteries. The gravimetric energy density has improved by a factor of 3 since their launch in 1991 and has now reached 0.25 kWh/kg, while cost has fallen by a factor of ten over the last two decades. So one is tempted to conclude that the battle is over: batteries have won, and we can forget about hydrogen for transportation.

But wait! Couldn't hydrogen play a role in aviation, where weight is such a crucial factor? After all, the gravimetric energy density of hydrogen is exceptionally high: three times the value for kerosene. This is especially important for long-haul flights, where the weight of the kerosene is roughly equal to the weight of the empty aircraft. Let us take a bold step and think of liquid hydrogen as a future fuel for aircraft. Most of the drawbacks which one faces when using liquid hydrogen in cars are no longer valid for use in aviation. For one thing, boil-off is much less of a problem: aircraft are airborne only for a limited amount of time, and moreover the low outside temperature at cruising altitude reduces the temperature difference with the liquid. In addition, refueling the cryogenic liquid, which may pose risks if done by laymen filling up the tank of their car, will be exclusively done by professionals at airports, thus reducing safety issues to the level of handling kerosene.

So, who knows, our grandchildren may take to the skies with hydrogen, not using the gas to lift an airship – slow like a snail – but to fuel the engines of a hydrogen airliner – at supersonic speed. ■