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Quantum entanglement and locality
Bound entanglement
The appearance of the tau-neutrino
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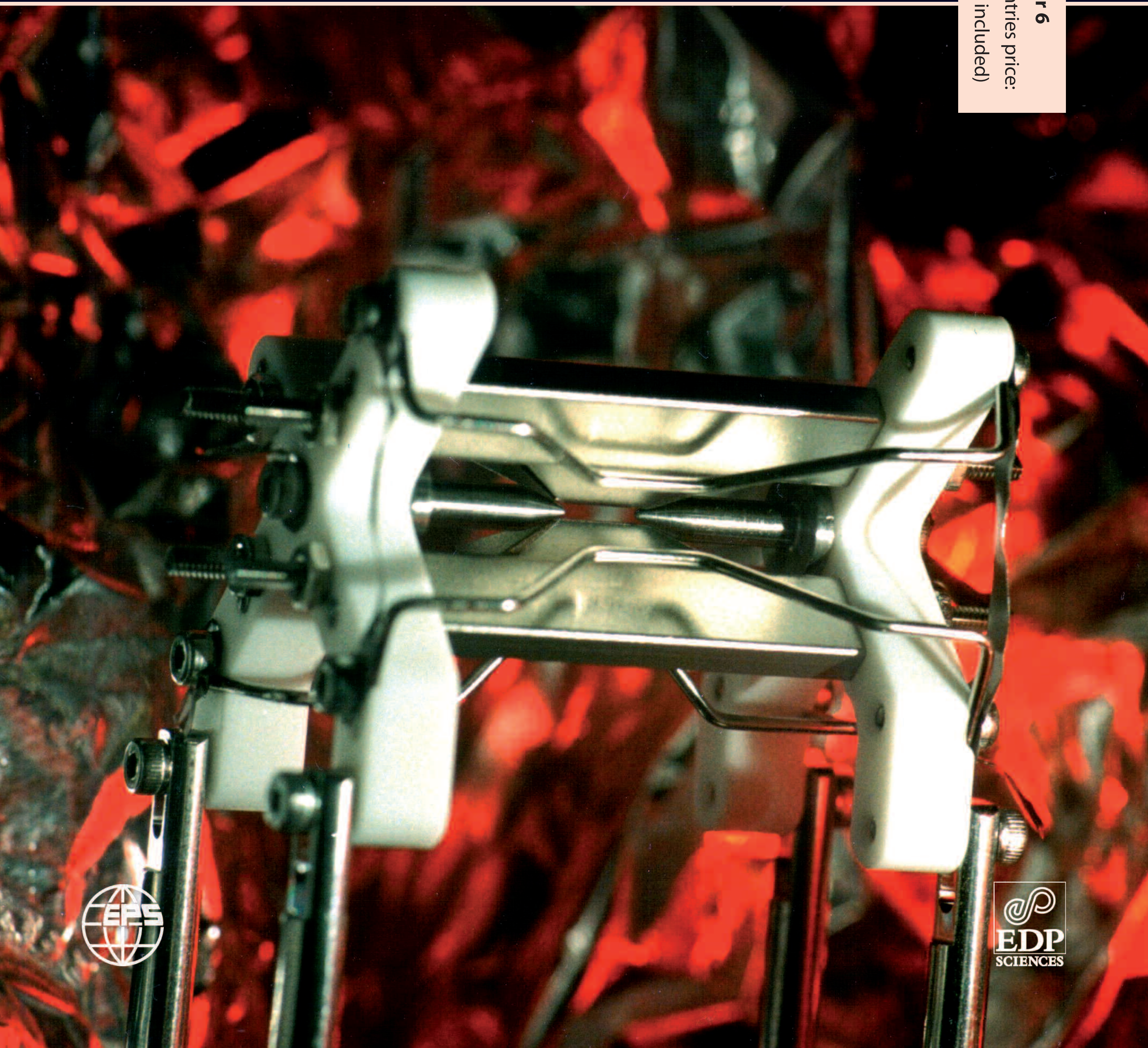

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Cover picture: Linear Paul trap where ions are confined to realize bound entanglement. © Institut fuer Experimentalphysik, Universitaet Innsbruck

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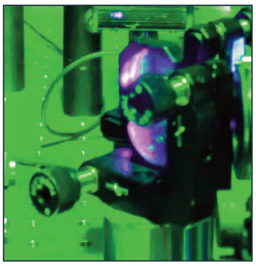
Vibrating liquids in space



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From **fundamental research to applications**

Scientific research is one of the first victims of budget restrictions. My impression is that many policy makers think that researchers trying to explain the world we live in do not serve any essential societal necessity. They are, of course, wrong. Scientific research, including physics, has made major contributions to social, economic and cultural development. Current challenges in energy, sustainable development and medicine require continued and increasing investment in scientific research.

While these arguments are obvious to scientists, we have let the policy makers impose an artificial distinction between fundamental and applied research. Scientists are forced to defend fundamental research, which is viewed as "curiosity driven", or in other words, for the fun of it, rather than research that has a "real value".

All research, whatever the time scale, is subject to the scientific method. When a researcher is confronted with an unexplained phenomenon, theories are proposed and tested through experiments. The experiments must be reproducible, and as free of bias as possible. With the scientific method, phenomena are explained based on empirical and measurable evidence. Another basic element of the scientific method is communication and peer review, allowing other researchers to test the results and propose alternative explanations.

Physics research is full of examples where discoveries at the fundamental level have led to applications. In 2007, the Nobel Prize in Physics was awarded to A. Fert and P. Gruenberg for their discovery of Giant Magnetoresistance, and in 2010 the Nobel Prize in Physics was awarded to A. Geim and K. Novoselov for groundbreaking experiments regarding the two-dimensional material graphene. It is interesting to note that in the Information for the Public published on the official site for the Nobel Prize (nobelprize.org), GMR applications " … have revolutionized techniques for retrieving data from hard disks. The discovery also plays a major role in various magnetic sensors as well as for the development of a new generation of electronics." For graphene, "...[its] exotic properties enable scientists to test the theoretical foundations of physics …[and] a vast variety of practical applications now appear to be possible including the creation of new materials and the manufacture of innovative electronics."

In fact, looking back at Nobel Prizes shows a strong correlation between discoveries at a fundamental level and technological advances that have had a real impact on modern society in all fields: energy, communication, medicine…

With the scientific method, the first thing that needs to be done is to propose an explanation that describes the phenomena. When you only have your eyes and ears, thunder *could* have been caused by clouds crashing together (rather than a shock wave of superheated gasses, resulting from lightning) - the theory. Then it is necessary to control the phenomenon in order to study it. Benjamin Franklin flying a kite in a thunder storm to determine whether lightning was electricity may not be the best example, but it is imaginative - designing the experiment to control the phenomena (including building the apparatus). An almost simultaneous development that accompanies this step is the ability to reproduce the phenomena. The first electric generator, the Faraday disk, produced a small but reproducible DC voltage. Consistent reproduction is important to validate research.

When researchers get this far, they create a virtuous circle, enriching and correcting theory, developing new instruments, techniques and materials, furthering our understanding of the natural world, often with advances in technology. When (and if) it becomes possible to reproduce the phenomena in a cost effective manner, then economic interests enter into play.

It is short sighted for policy makers to oppose fundamental and applied research and to insist on an immediate return on investment. All research uses the scientific method - to explain, control and reproduce - and cannot go faster than our ability to understand our universe, step by step. More resources need to be devoted to scientific research if policy makers want solutions. The scientific method and its impact on our societal values is an important argument for scientists to defend research, whatever the time scale. ■

David Lee, Secretary General of the EPS

Executive Committee Meeting

San Sebastian(ES), 1-2 Oct 2010 - Summary

The EPS Executive Committee met at the ***Donostia International Physics Center*** *hosted by Pedro Miguel Echenique Landiribar.*

The participation of EPS in Initiative for Science in Europe and the EIROForum was discussed.

The EPS - Quantum Electronics and Optics Division has proposed the **International Year of Light** to be held in 2015. EPS projects to launch the activity with a workshop EPS/SIF in Varenna (I), a presentation will soon be published in EPN.

After on-site consultation in July, M. Knoop and C. Latimer made first proposals about **Secretariat organisation**, other steps to follow.

The ExCom was informed about the ongoing work of the **Strategy Working Group** (SWG), which will hold its 4th meeting in the first week of October. Proposals will be discussed in a **special Council session**, scheduled on Saturday 20 November, 2010, in Amsterdam.

Regarding the economic situation of EPS, the **net income 2010** has decreased due to a drop in contribution by MS, **extra spending** will be necessary to cover the costs of SWG and special council meeting. A detailed budget for 2011 can only be prepared after the November council session.

In an Open Session, the ExCom met and discussed with Carlos Hidalgo, chair of the Plasma Physics Division, and Jan Mostowski, new editor in chief of the European Journal of Physics.

EPL will celebrate its 25th **anniversary** with a symposium to be held at the Bavarian Academic of Science/ Munich from 3-4 May, 2011.

In 2011, the joint **EPS-ASEPS** workshop will be organised together with the EPS General Conference in Wroclaw (PL); the program committee is chaired by Prof. Jerzy Langer (Polish Vice-minister of Science).

The third year of EPS study on the **Bologna process** has started to investigate the doctorate level; a conference will be held in June 2011 together with GIREP.

The next "Conférence exceptionnelle" will be given by J-P. Changeux from Collège de France on 9 December 2010 at UHA, Mulhouse.

The ExCom proposes to prepare a position paper about **science assessment** with the input of MS.

It has been decided to report the 2011 council to 1 - 2 April 2011, in Mulhouse. ■

Martina Knoop

Report from the

EPS Plasma Physics Division

The 2010 EPS Plasma Physics Conference was in Dublin in June and the 2011 one will be held in Strasbourg (France) from June 27 – July 1, 2011

Hannes Alfvén Prize 2010

This prize is awarded to **Allen Boozer** (Professor, Columbia University) and **Jürgen Nührenberg** (Professor, Max-Planck Institut für Plasmaphysik and Greifswald University) *"for the formulation and practical application of criteria allowing stellarators to have good fast-particle and neoclassical energy confinement"*.

The tokamak and the stellarator are two major candidate concepts for magnetically confining fusion plasmas. They were both conceived in early 1950's, but the tokamak developed more rapidly because of its intrinsically favourable confinement properties. Indeed, the stellarator seemed fundamentally unable to confine energy and collisionless alphaparticle orbits well enough for a fusion reactor.

In the 1980's, however, Allen Boozer and Jürgen Nührenberg developed methods for tailoring stellarator magnetic fields so as to guarantee confinement comparable to that in tokamaks. Allen Boozer introduced a set of magnetic coordinates, now named after him, in which the description of 3D-shaped magnetic fields is particularly simple. He went on to show that if the magnetic field strength |B| is symmetric in these coordinates (so-called quasisymmetry) then the guiding-centre orbits and the neoclassical confinement properties are equivalent to those in a tokamak. In pioneering calculations a few years later, Jürgen Nührenberg showed that such magnetic fields can indeed be realised in practice, as can other configurations which have equally good confinement without being quasisymmetric.

There is an unexpected vastness of configurational possibilities for toroidal plasma confinement, where the limit is likely to be set by turbulence rather than neoclassical losses. In addition, quasi-symmetry should facilitate the development of strongly sheared rotation with direct impact in the control of turbulent transport.

Moreover, Jürgen Nührenberg showed that a number of other properties of the magnetic field can also be optimised simultaneously, allowing high equilibrium and stability limits to be achieved and thus opening up a road to an inherently steady-state fusion reactor.

The ideas of Allen Boozer and Jürgen Nührenberg have revolutionised stellarator research. They have already partially been confirmed on the W7-AS and HSX stellarators, and provide the basis for the world's largest stellarator under construction, Wendelstein 7-X. The award of the 2010 Hannes Alfven Prize to these two leading scientists underlines the development of understanding and transfer of knowledge in plasma physics.

Plasma Physics Innovation Award 2010

This EPS Prize is awarded to **Uwe Czarnetzki**, professor at Ruhr-Universität Bochum, *"for his outstanding contributions in the discovery of the Electrical Asymmetry Effect, its scientific characterization and for its development up to the level of successful industrial application"*.

The energy of ions impacting surfaces during plasma processing is crucial in determining both the properties of materials being deposited by plasmas and for the control of the etching of thin films. The independent control of the ion energy and the plasma density has been the object of intense industrial research. Current technologies for modifying the ion energy rely on the geometry of the plasma processing chamber or by applying low and high frequency RF power that is not phase locked. These techniques are either not applicable to some situations or have only been partially successful. The "Electrical Asymmetry Effect" allows the ion energy and plasma density to be decoupled. If the RF power applied to a plasma chamber is comprised of a phase locked fundamental and its second harmonic, the ion energy is a linear function of the phase angle between the two. This simple, but previously overlooked technique has shown to be an enabling technology for future materials and plasma applications.

The method has been patented and is presently used *e.g.* by leading manufacturers of large area solar cells and has resulted in unsurpassed quality and homogeneity of the devices. In addition to the "Electrical Asymmetry Effect", Uwe Czarnetzki is internationally renowned for his many important contributions in the areas of laser based plasma diagnostics and gas discharge physics. For all of these outstanding contributions to low temperature plasmas, the European Physical Society bestows its 2010 Plasma Physics Innovation Prize to Uwe Czarnetzki.

PhD Research Award 2010

This EPS PhD prize is a key element of the PPD activities to recognise exceptional quality of the work carried out by young physicists. The jury nominated 4 award winners from an impressively high quality of candidates. The 2010 citations in alphabetical order are:

Xavier Davoine for his research on intense ultra short X sources obtained by acceleration of a class of electrons in the wake field of a laser pulse, improving the numerical procedure to model the electron dynamics.

Guilhem Diff-Pradalier for a fundamental discussion of the formalism needed to describe turbulence and transport in magnetized plasmas, including a collision operator in the Gysela gyrokinetic code that could modify the characteristics of the turbulence.

Emeric Falize and **Bérénice Loupias** for their investigation of similarities between laser induced plasmas and astrophysical systems and for the description of a set of diagnostics for laser plasmas aimed at demonstrating the possible astrophysics character of plasma jets in laser induced plasma formation.

Peter Manz for his comprehensive analysis in turbulence in magnetized plasmas, exploring the interplay between flows, electric fields and fluctuations. ■

C. Hidalgo,
Chair, EPS Plasma Physics Division

2010 Nobel Prize

for the discovery of graphene

We all expected this would happen eventually, but it came sooner than expected. Six years after graphene (a single layer of carbon atoms) was first isolated, the two discoverers of this "wonder material" receive a Nobel Prize.

Theorists have written about carbon monolayers since 1947. It was generally believed that such a material could not exist in nature, because the two-dimensional crystalline order would be unstable. The intriguing properties of carbon monolayers (massless electrons and holes at low doping, with a quasi-relativistic dynamics described by the Dirac equation) remained therefore a topic of purely theoretical interest. The calculation of the band structure of a carbon monolayer was the type of problem you gave to students as an elementary application of the tight-binding method, with a *caveat* that this exercise had no physical realization.

▼ The Nobel laureates in a pensive mood. Three countries share in the glory: Both Konstantin Novoselov (right) and Andre Geim are Russian born and educated, but also spent part of their formative years in The Netherlands, before settling down in the United Kingdom. Trivia: Novoselov is the youngest Nobel laureate in Physics since 1973, while Geim is the only Nobel laureate to have also won the Ig Nobel Prize (for levitating a frog). [Photograph courtesy of Manchester University.]

All of this changed in 2004, when Andre Geim and Konstantin Novoselov, with colleagues at Manchester University, showed that carbon monolayers do in fact exist as a stable form of carbon. Their method of fabrication was outside of the beaten path, even a bit idiosyncratic. Instead of the high-level techniques towards the production of few-layer graphite (atomic force microscopy by Philip Kim from Columbia University, epitaxial growth by Walt de Heer from Georgia Tech), Geim and Novoselov used adhesive tape to peal off a single layer from a piece of graphite. It should not work, but it did. As Kim graciously admits in his public lectures: "We were scooped by a piece of Scotch tape".

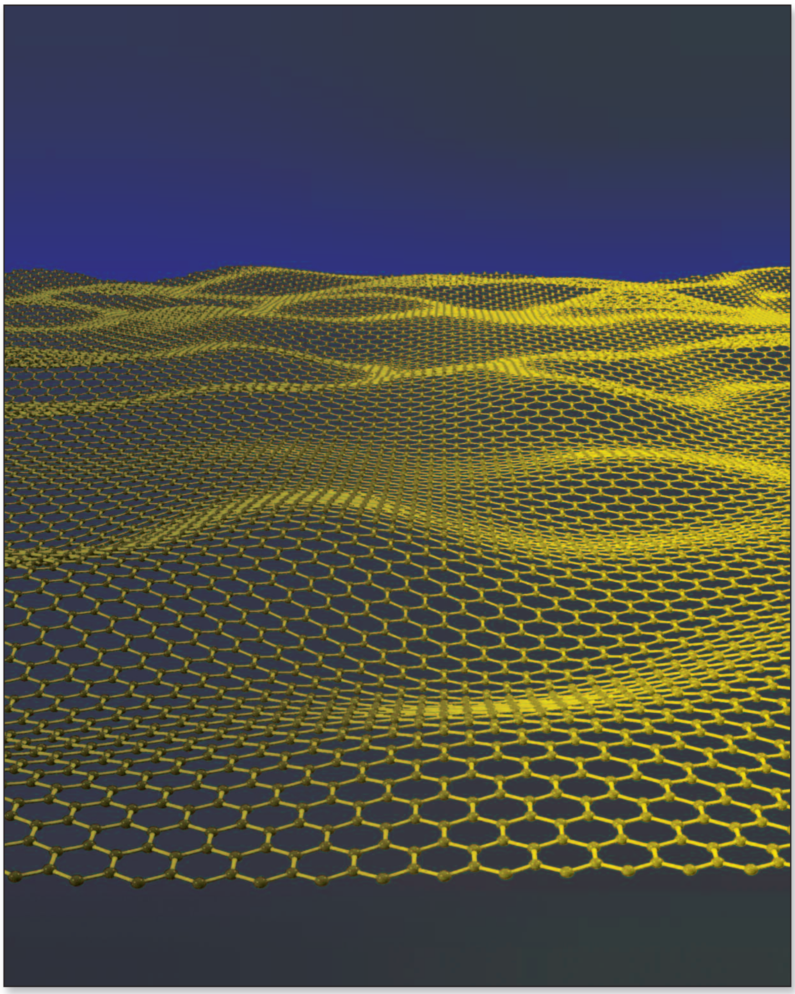
The single layer flakes are very rare in the debris of graphite flakes, typically there are just a few μm^2 size monolayers scattered randomly in a cm^2 area. Searching for the monolayers is therefore quite like trying to find a needle in a haystack. This explains why earlier attempts (notably by Rodney Ruoff from Washington University) to find monolayers using probes with atomic resolution had failed. The optical detection of monolayers was the key innovation of the Manchester group that made the discovery of graphene possible. Graphene flakes can be located among the multilayers on a silicon substrate because of their slightly different colour under an optical microscope. Once located, atomic force microscopy could verify that these flakes were indeed monolayers. While atomic force microscopy can count the number of layers in the flake and is sufficient to demonstrate that a monolayer has been isolated, to actually confirm 2D electron dynamics one needs to observe the quantum Hall effect. That successful confirmation was reported in 2005 by the Manchester group. Kim and his group could provide an independent confirmation, after they had switched to the adhesive tape method of fabrication. This method has now been adopted by laboratories all over the world, and has produced a wealth of new phenomena involving electronic, optical, mechanical, and chemical properties. This is my list of favorite breakthroughs (incomplete and biased by my own interests):

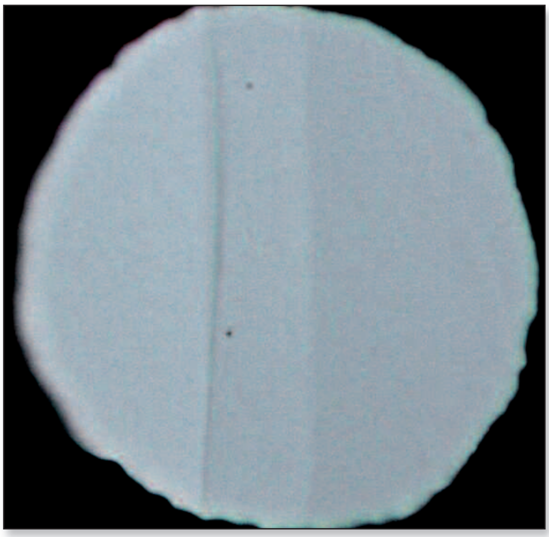
- *Graphene is the first two-dimensional crystal.* While strictly 2D crystalline order is unstable due to thermal fluctuations, graphene can exist as a stable sheet of carbon atoms with relatively weak ripples and few crystal defects. Before 2004, atomic monolayers of carbon were only known to exist in the rolled-up form of nanotubes or fullerenes. In graphite, 2D layers exist but not in isolation. The coupling between the layers in graphite is relatively weak compared to the carbon-carbon bond within the layers, and yet this weak coupling destroys the special properties of 2D motion. In particular, the zero-mass property of the conduction electrons is unique for the single layer – it is lost in the double layer.
- *Graphene is representative of a whole class of two-dimensional crystals.* The "Scotch tape" method invented by the Manchester group to isolate

graphene (mechanical exfoliation followed by optical detection), can be used to extract atomic monolayers from a variety of strongly layered materials. That these monolayers are stable in air at room temperature, without the protection offered by a 3D structure, was completely unexpected.

- *Graphene exhibits two-dimensional dynamics at room temperature.* Before the discovery of graphene, 2D electron dynamics was studied extensively in semiconductor heterojunctions. Low temperatures (a few Kelvin) are needed for these experiments, because the dynamics is no longer two-dimensional at higher temperatures. Graphene remains strictly 2D at room temperature, retaining its structural stability and good conductivity. A striking demonstration of 2D dynamics at room temperature was the observation of the quantum Hall effect at 300 K.
- *Graphene has massless carriers of electrical current.* The periodic potential of the carbon atoms, arranged on a honeycomb lattice, has a unique effect on the electron dynamics: the effective mass tends to zero at low energies. This surprising property of a carbon monolayer goes back to its first theoretical study in 1947 by Philip Wallace (1915–2006), and it plays a role in the 1D motion in carbon nanotubes. But the most striking consequences of massless dynamics require two spatial dimensions, and they remained of purely theoretical interest before the discovery of graphene.

▼ **FIG. 1:** Artists impression of a carbon monolayer, based on data obtained by transmission electron microscopy of a freely suspended graphene sheet. The ripples have a typical height of 1 nanometer and width of 25 nanometer. [Illustration by Jannik Meyer, Ulm.]





▲ **FIG. 2:** The eye can see the difference between a single layer of carbon atoms (central strip) and two layers (region to the right). Each atomic layer absorbs 2.3 percent of incident light, determined by the fine structure constant. [Photograph by Rahul Nair, Manchester.]

Practical applications of graphene are likely to follow. Geim expects that "it has all the potential to change your life in the same way that plastics did". It is too early to decide at this stage whether or not graphene will fulfill this promise of "wonder material". However, the importance of Geim and Novoselov's pioneering work for fundamental physics is already quite evident. More than half a century of theoretical studies of a system which was not believed to exist, have now found a realization in nature. ■

Carlo Beenakker,
Instituut-Lorentz, Leiden University

About the author

Carlo Beenakker is a condensed matter theorist at the Lorentz Institute of Leiden University, The Netherlands. He is the recipient of an ERC Advanced Investigator award for the study of graphene.

More about graphene

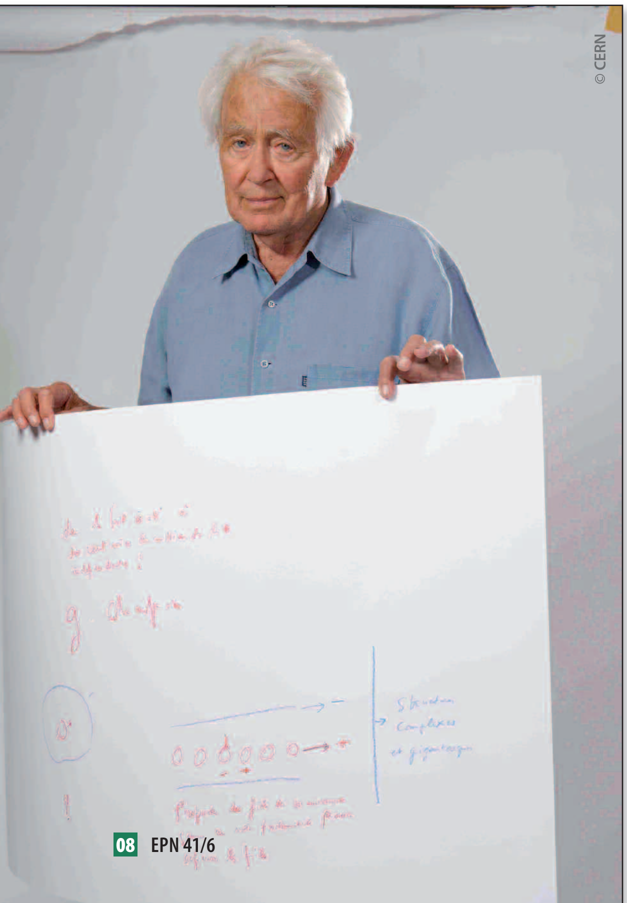
Can be found in the feature "Graphene, new physics in two dimensions" by N.M.R. Peres in *Europhysics News* **40/3**, 17 (2010).

Georges Charpak,

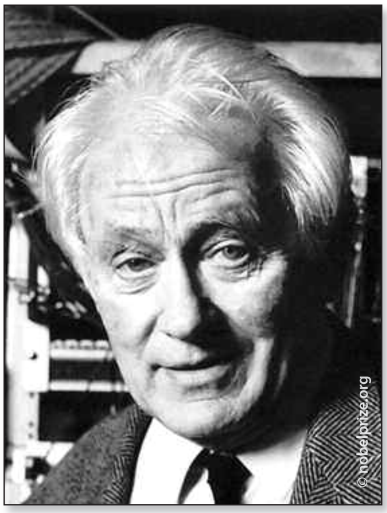
Nobel laureate 1992 (1924 – 2010)

Born in Poland, Georges Charpak came to France at the age of 7. During world war two, he engaged himself early against the invaders and was deported to the concentration camp of Dachau.

He fortunately came back alive, obtained the French citizenship in 1946 and graduated from one of the most prestigious engineering schools in France, the "Ecole des Mines de Paris". His carrier as a research physicist started in 1948 at CNRS (French National Centre of Scientific Research), when he entered Frédéric Joliot's laboratory at Collège de France in Paris. G. Charpak defended his PhD thesis in 1955 and from then on spent most of his carrier at CERN in Geneva until retirement in 1989, before getting his Nobel Prize in 1992. After 1989, he became professor at the engineering School of Industrial Physics and Chemistry of Paris (ESPCI) directed by another Nobel laureate, P-G de Gennes.



As a Physicist, the work of G. Charpak concentrated on the detection of high-energy particles. He started along the Geiger line and built a chamber filled with a properly chosen gas and crossed by a wire held at a high voltage. Any charged particle speeding through the gas generates ions, which are collected by the nearby wire and then give an electric signal. With its higher sensitivity, this detector, even in its first form, replaced rapidly the previous bubble chambers. G. Charpak invested himself in developing this kind of detector, first by mounting a large set of parallel wires at high voltage, allowing to detect where, along the direction perpendicular to the wires, the charged particle was crossing the gas-filled chamber. The next step was of course to put two parallel planes of parallel wires with the wires of one perpendicular to the wires of the other, allowing then locating the passing-by charged particles. Finally, with several sets of double planes of wires, the trajectories can be imaged with high precision and sensitivity. This wide family of detectors, used all around the world, have been the source of numerous discoveries in high-energy particle physics and of endless applications from astrophysics to medicine. Their creative and efficient development by Georges Charpak, which concerned the geometries of the chambers, the gas optimisations as well as the low noise electronic equipments, has fully justified the choice of the Nobel Jury in 1992. The ideas of G. Charpak are still largely used in the LHC (Large Hadron Collider), the latest machine built in CERN.



Retirement did not stop the activities of G. Charpak. In the 90s, he used the performances of his detectors to improve the medical radiographic equipments, decreasing by several orders of magnitude the irradiation needed to get excellent X-Ray images through living bodies. He also involved himself into the renewal of science teaching, in which the children enter into science by hands-on practice. A wide operation called "La Main à la Pâte" started in France in 1996, with the strong support of the French Academy of Sciences, and involved several hundreds primary school teachers all over the country. These ideas are still widely developed and diversified in France and several other countries.

With the loss of Georges Charpak, the world misses not only one of its most creative and prestigious scientists but also a true humanist deeply concerned by the future of our planet and its inhabitants. ■

The EPN Editors

2010 Conference of the European Platform of Women Scientists
"Women in Present and Future European Research"
Brussels, 10-11/6/ 2010

The European Platform of Women Scientists (EPWS) (www.epws.org) is an umbrella organisation bringing together networks of women scientists and organisations committed to gender equality in all science research disciplines across the European Union (EU) as well as in the countries associated to the EU Framework Programmes for Research and Technological Development.

Legally established as an international non-profit organisation under Belgian law in November 2005, it is establishing links between scientists and policy makers. Its main areas of activity are: networking and membership; research policy and advocacy; information and public relations; private and public Partnerships. EPWS represents 104 member organisations and 78 individual members and gives a voice to 12,000 women scientists. 36% of its member networks' disciplines are Natural Sciences and Engineering, 29% are Social Sciences and 28% may be grouped as Humanities and Multidisciplinary General. Physics is very well represented: of the ten EPWS Board of Administration members, three are physicists. The large number of women scientists in its member networks, combined with the wide experience and expertise of its members on the Women and Science issues, make EPWS a key partner in this domain.

From its creation until October 2009, EPWS was totally funded as an EU project; it is now operating by relying on its members' voluntary efforts.

EPWS held its General Assembly and **Annual Conference "Women in Present and Future European Research"**, in Brussels, Belgium, on June 10th and 11th 2010, in the Royal Belgian Museum of Natural Sciences. The keynote lecture was given by Luisa Prista, Head of the Unit "Scientific Culture and Gender Issues", DG Research, on "New Developments in the European Research Area (ERA) for Women in Science".

The Conference reported on recent and current projects from across Europe to improve the gender balance in science. Several important European projects supported by Directorate General (DG) Research under the 7th Framework Programme, tackling the issue of gender balance in science, were included as well as initiatives encouraging girls into science, technology, engineering and mathematics. There were presentations on PRAGES, genSET, MASIS, HELENA, GENDERA, UNICAFE, DIVERSITY, JUNO and many more.

About 60 representatives of European organizations of women scientists from 13 countries across over Europe attended the conference, enabling a lively market place of networks, ideas and partnerships. The participants had the opportunity to present their work both through participating in discussion sessions and through a poster exhibition highlighting their activities related to the Conference topics.

The initiatives of the Institute of Physics, United Kingdom, to interest girls to science and to address the under-representation of women in university physics were a source of inspiration for the participants.

EPS kindly supported two of the Board of Administration members by covering their travel expenses to the Brussels Conference and EPWS is grateful for this generosity. As gender issues are also a concern for the European Physical Society, we are confident that a fruitful collaboration between these two organisations will be pursued. ■

▲ Conference dinner

Claudine Hermann,
Vice-president of EPWS,
president of honor of the French association Women and Science (Femmes & Sciences)

Ann Marks,
Member of the EPWS Board of Administration, member of the Council of the Institute of Physics, United Kingdom.

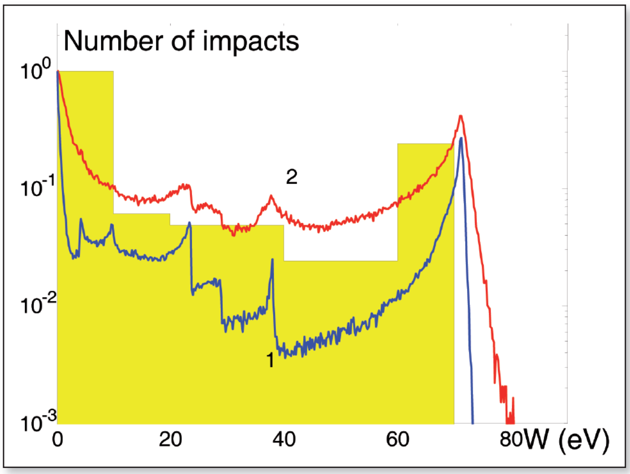
▼ Poster session

Highlights from European journals

APPLIED PHYSICS

Electrical breakdown in space-borne microwave equipment

Electrical breakdown (multipactor) constitutes a severe problem in many modern microwave systems, *e.g.*, space borne communication equipment. The breakdown discharge tends to generate noise, change the device impedance, heat the device walls and may permanently damage the devices. The basic physics involved in the multipactor breakdown phenomenon is well known. However, new applications give rise to situations where previous results concerning breakdown are not applicable. The concomitant uncertainties in predicted breakdown power levels makes it necessary to allow for large safety margins in device specifications and/or to use expensive test procedures.



▲ **Example of a comparison between theoretical and experimental results for the distribution of impact energy of discharge electrons at the outer waveguide electrode. Lines 1 and 2 correspond to different theoretical predictions and are superimposed on the experimental results.**

To improve the situation, a strong effort has been made within a close collaboration between Centre National d'Etudes Spatiales in Toulouse, France, Chalmers University of Technology, Gothenburg, Sweden, Institute of Applied Physics, Nizhny Novgorod, Russia and General Physics Institute, Moscow, Russia. The present paper reports on recent results obtained for coaxial waveguides, which are commonly used for transmission of microwaves. A comprehensive analysis is made of multipactor breakdown thresholds in such structures using theoretical modelling and numerical simulations, which are corroborated with results of detailed experiments.

The results provide new knowledge and prediction capability concerning multipactor breakdown in microwave systems involving coaxial waveguides and should be an important input for an upgrading of the document for European Cooperation for Space Standardization. ■

▮▮▮ **I.A. Kossyi**, **G.S. Luk'yanchikov**, **V.E. Semenov**, **N.A. Zharova**, **D. Anderson**, **M. Lisak** and **J. Puech**, 'Experimental and numerical investigation of multipactor discharges in a coaxial waveguide', *J. Phys. D: Appl. Phys.* **43**, 345206 (2010).

LIQUID PHYSICS

Bose condensation gives new insight into turbulent advection

Passive scalar turbulence describes the advection and diffusion of a scalar quantity (such as temperature or pollutant concentration) in a turbulent flow. It was rigorously proven in the 1990's that the Kraichnan model, now widely hailed as the "Ising model of turbulence", leads to statistical intermittency and anomalous scaling of the advected field, which means power law behaviour of the structure functions of the scalar with scaling exponents ζ_N depending in a nonlinear way on their order N. The emergence of anomalous scaling was traced to the existence of statistical integrals of motion showing up in the evolution of Lagrangian fluid particles and exponents ζ_N identified with the highest scaling dimension or degree of the corresponding so-called "zero modes" (homogeneous functions of interparticle distances, whose average in the N-particle configurational space is left invariant by the dynamics).

Analytical computations of zero modes and their degrees were, up to now, mostly done using perturbative methods around limiting values of parameters for which anomalous scaling disappears. It is shown in this paper that scaling dimensions of zero modes can be recast as eigenvalues of a many-body pseudo-Hamiltonian describing the dynamics of the Lagrangian particles in an appropriate comoving frame. A variational estimate for ζ_N is then obtained by using techniques borrowed from condensed matter physics and assuming Bose condensation of particles. A connection of zero modes with the extremal events leading to the formation of fronts of the scalar, as caught by the instanton formalism, is also established.

By bridging up the gap between the two most powerful tools (zero modes and instantons) introduced these last years in the study of the inertial range intermittency in turbulent systems, this works revives the hope that they might help us to unravel, once, the whole complexity of incompressible 3D Navier-Stokes turbulence. ■

T. Dombre,
'Bose-like condensation of Lagrangian particles and higher-order statistics in passive scalar turbulent advection', *EPL* **91**, 54002 (2010).

BIOPHYSICS

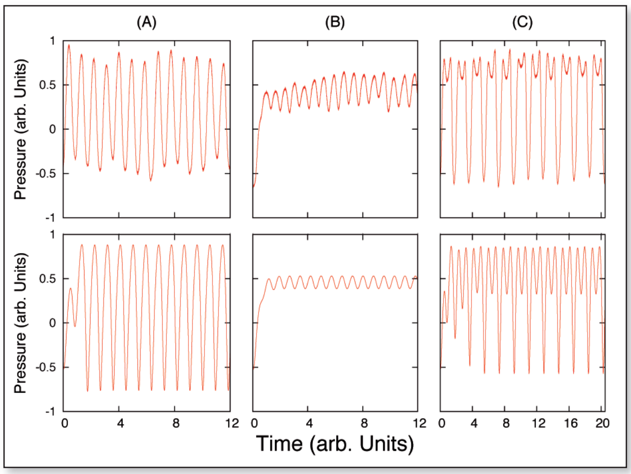
Dynamical origin of complex motor patterns

Many motor patterns in biology are surprisingly simple, particularly taking into account that they are generated by complex neural networks. During song, for example, some songbirds have to generate periodic fluctuations in their air sac pressure and syringeal muscle tension in order to achieve sounds with the adequate acoustic properties. For the case of domestic canaries, the different respiratory patterns used during song were found to be sub-harmonic solutions of a simple, low dimensional dynamical system. Yet, these gestures are generated by thousands of neurons operating in a non-synchronous regime. How can the average activity present the precise, non-trivial features of the solutions of a low dimensional nonlinear dynamical system?

Inspired by this example, we address the general issue of the emergence of low dimensional, non-trivial dynamics out of large, complex interacting units.

In the spirit of classical statistical mechanics, the equations obeyed by the order parameter of a population of globally coupled nonlinear units are derived. The analysis allows showing that non-trivial yet low-dimensional dynamics is possible in average, even in a non-synchronic regime, providing a new mechanism for dimensionality reduction in the dynamics of complex systems. ■

▲ **The average activity of a large set of forced, globally coupled excitable units fits the subtleties of the air pressure patterns used by domestic canaries during their song. Each excitable unit is the dynamical caricature of excitatory and inhibitory neural subpopulations in the neural song pathway. Upper panels show different experimental gestures. Lower panels display the simulations.**



L.M. Alonso, **J.A. Alliende** and **G.B. Mindlin**,
'Dynamical origin of complex motor patterns', *Eur. Phys. J. D* **60**, 361 (2010).

NUCLEAR PHYSICS

Cold fusion mechanism in nanoscale catalysis?

The well-understood mechanism of muon-catalyzed nuclear fusion is used for a fundamental understanding of H_2O_2 catalysis by nanogold, including the substantial enhancement by Au-Pd. Consider the muon-catalyzed fusion using *t* and *d*. At the Ramsauer-Townsend (R-T) minimum of the $d\mu$ and $t\mu$ elastic scattering, $dt\mu$ molecules form through strong resonances. The Coulomb barrier shrinks and *d-t* fusion results. In gold catalyzed H_2O_2 the Au^- anion is first formed at the R-T minimum of the electron-Au elastic cross section. Single and double water molecules can attach to the Au^- anion through strong resonances with large rates forming $Au^-(H_2O)_1$ and $Au^-(H_2O)_2$ anion-molecule complexes. The Coulomb barrier shrinks. Because the experiment used nanogold supported on Fe_2O_3, a chemical reaction between H_2O and O_2 resulted in H_2O_2 formation, releasing the Au^- catalyst.

A similar analysis applies to the electron-Pd elastic scattering but with the caveat that the Pd electron affinity is slightly smaller than and R-T minimum is deeper than and extends beyond that of gold. Hence, this rich environment in minima and resonances facilitates attachment of water molecules to Au^- and Pd^- anions, yielding H_2O_2 through multiplicative catalyses.

Electron-electron correlations and core-polarization interactions are crucial for the existence and stability of most negative ions. These physical effects are embedded in our calculations. Indeed, atomic negative ions play an essential role in cold nuclear fusion and in catalysis, a chemical reaction. Au, Pt, Pd and Y atoms can be used in various combinations.

This discovery ushers in new frontiers of efficient design and synthesis of novel functional compounds and catalysts for various chemical reactions, impacting many industries. The controversial Fleischmann–Pons "cold fusion" experiment can now be understood. It used Pt-Pd electrodes and has generated attention in recent APS NEWS articles. ■

A.Z. Msezane, **Z. Felfli** and **D. Sokolovski**,
'Novel mechanism for nanoscale catalysis', *J. Phys. B: At. Mol. Opt. Phys.* **43**, 201001 (2010).

QUANTUM PHYSICS

Long-time behaviour of **macroscopic quantum systems**

The renewed interest in the foundations of quantum statistical mechanics in recent years has led us to study John von Neumann's 1929 article on the quantum ergodic theorem (QET). We have found this almost forgotten article, which until now has been available only in German, to be a treasure chest, to be much misunderstood and very relevant to the recent discussion on the general and abstract reasons why, and the exact sense in which, an isolated macroscopic quantum system will approach thermal equilibrium from (more or less) any initial state. In his paper, von Neumann studied the long-time behaviour of macroscopic quantum systems. His main result, the QET, expresses so-called "normal typicality": for a typical finite family of commuting macroscopic observables, every initial wave function $\psi(0)$ from a micro-canonical energy shell so evolves that for most times t in the long run, the joint probability distribution of these observables obtained from $\psi(t)$ is close to their micro-canonical distribution.

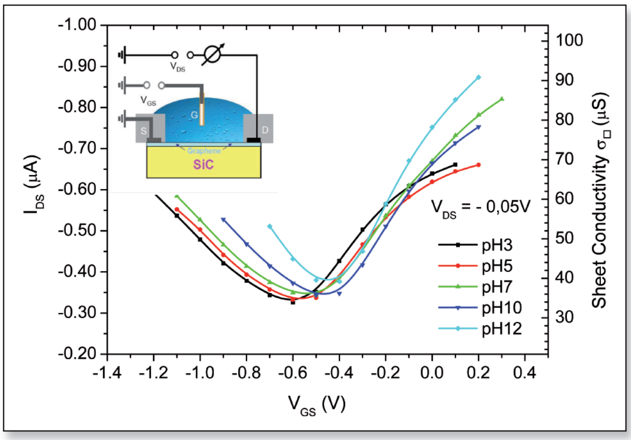
In our commentary, we provide a gentle introduction to the QET and discuss its relevance to the approach to thermal equilibrium. There is, in fact, no consensus about the definition of thermal equilibrium for a quantum (or even a classical) system in microscopic terms; the main divide in the literature lies between the "ensemblists" who regard thermal equilibrium as a property of an ensemble (or a mixed state) and the "individualists" who regard thermal equilibrium as a property of an individual system (in a pure state). As we explain, von Neumann's concept of equilibrium is influenced by both views but mainly based on the individualist view, a view that has gained ground recently. ■

■■■ **S. Goldstein**, **J.L. Lebowitz**, **R. Tumulka** and **N. Zanghì**, 'Long-time behaviour of macroscopic quantum systems - Commentary accompanying the English translation of John von Neumann's 1929 article on the quantum ergodic theorem', *Eur. Phys. J. H* **35**, 173 (2010).

APPLIED PHYSICS

Field effect transistors of epitaxial graphene on SiC

Graphene is at date the most recognized new candidate for the electronic material of the future, the 2010 physics Nobel prize being only the ultimate indication of this fact to the public. As a two-dimensional electronic system of only one atomic layer with a correspondingly low number of charge carriers per area, it makes the material extremely sensitive to charge exchange with the outside world. This is blessing and curse at the same time: high electronic sensitivity for adsorbates is useful for chemical sensing if it can be selectively controlled; it is extremely annoying, however, for stable switching devices. In any case, understanding the interfaces between graphene, its (unavoidable) substrate onto which it is prepared, and the ambient in contact with its surface is vital for developing electronic devices based on the material.



▲ **This figure shows the so-called transfer characteristics of a Solution Gated Field Effect Transistor (SGFET) fabricated on epitaxial graphene on silicon carbide. The current through the transistor channel from the source to the drain contact, driven with constant source-drain voltage, is plotted vs. the control voltage applied between the source and the gate. The minimum of each curve belongs to the situation where the Fermi level in the graphene coincides with the Dirac energy. The control voltage corresponding to this condition shows a pH dependent shift due to varying protonation of the graphene surface. Insert: Schematics of the device and the electrical circuitry adopted in the experiment.**

The article at hand is focussing on this topic, adopting a special transistor design, the so-called solution gated field effect transistor, for investigating epitaxial graphene on silicon carbide in contact with an aqueous medium. The detailed analysis of the device's transfer characteristics yields a surprisingly high charge carrier mobility in the graphene sheet, but also reveals the important role of silicon carbide surface states at the graphene interface. ■

■■■ **J. Ristein**, **W. Zhang**, **F. Speck**, **M. Ostler**, **L. Ley** and **T. Seyller**, 'Characteristics of solution gated field effect transistors on the basis of epitaxial graphene on silicon carbide', *J. Phys. D: Appl. Phys.* **43**, 345303 (2010).

CONDENSED MATTER

Nernst effect and diamagnetic response in superconducting cuprates

One of the central puzzles of the high-temperature cuprate superconductors is the nature of the *pseudo-gap* regime that extends from the parent Mott insulator to at least optimal doping and up to several hundred degrees Kelvin. Though it is unlikely that the entire pseudo-gap region is directly related to superconductivity, there is compelling experimental evidence of anomalously strong superconducting fluctuations within the pseudo-gap.

Two phenomena have particularly high sensitivities to the presence of superconductivity, even local or fluctuating one: the diamagnetism and the Nernst effect. The diamagnetic part of field-induced magnetization can reveal the presence of even isolated superconductivity inclusions, as they expel magnetic field. The Nernst effect is a thermal analogue of the conventional Hall effect – the transverse voltage generation in response to the heat current flow in a magnetic field. The Nernst effect in metals is typically very weak; however, in the presence of superconductivity it is greatly enhanced due to the thermal drift of vortices, which induces voltage via the Josephson relationship.

We examine the possibility that the experimentally observed enhancement of superconducting fluctuations above the superconducting transition temperature in the underdoped cuprates is caused by *stripes* – an intrinsic electronic inhomogeneity, common to hole-doped cuprates. By evaluating the strengths of the diamagnetic response and the Nernst effect within a striped SC model, we find results that are qualitatively consistent with the experimental observations. We make a prediction for anisotropic thermopower in detwinned samples that can be used to further test the proposed scenario. ■

I. Martin and **C. Panagopoulos**,
'Nernst effect and diamagnetic response in a stripe model of superconducting cuprates', *EPL* **91**, 67001 (2010).

CONDENSED MATTER

A description of **the jamming transition** in soft particulate matter

This paper illustrates how the tools of equilibrium statistical mechanics can help explain a different set of natural phenomena – the physics of systems far-from-equilibrium, such as the jamming transition in granular matter. When S.F. Edwards from Cambridge University proposed a thermodynamic formulation for grains, the community of statistical physics received it as attractive and innovative. However, since there are no first principle justifications of Edwards' ideas they were also viewed with some degree of scepticism. Since the publication of Edwards' original work over 20 years ago, the scientific community has debated the possibility of its validity. Edwards' ideas consist of proposing a statistical ensemble of volume and stress fluctuations through the thermodynamic notion of entropy, compactivity and angoricity (two temperature-like variables). We find that Edwards' thermodynamics correctly describes our numerical and theoretical study of the jamming transition (J-point).

Using the ensemble formalism we elucidate two questions regarding the jamming transition: (i) The thermodynamic approach predicts the order of the jamming phase transition by showing the absence of critical fluctuations at jamming in observables like pressure and volume. (ii) We also show that the thermodynamic viewpoint allows one to calculate the physical observables near jamming providing a characterization of jammed solids at the J-Point.

The fact that a simple set of thermodynamics postulates gives rise to the correct results for the case of granular materials driven through the jamming transition may have implications in other fields where out of equilibrium systems are the norm. ■

Kun Wang, **Chaoming Song**, **Ping Wang** and **H.A. Makse**,
'Angoricity and compactivity describe the jamming transition in soft particulate matter', *EPL* **91**, 68001 (2010).

Short news

▸ Forum for Local Probe Microscopy

The report on the Forum for Local Probe Microscopy, held from 15 to 18 March 2010 in Mittelwhir (France) can be asked to one of these two organisers: François Vonau, Institut de Science des Matériaux de Mulhouse (IS2M), francois.vonau@uha.fr, and Jean-Pierre Bucher, Institut de Physique et Chimie des Matériaux de Strasbourg (IPCMS), bucher@ipcms.u-strasbg.fr

▸ A European school on Magnetism to come

The next "European School on Magnetism" (ESM) will take place in Targoviste, Romania, from August 22 to September 2, 2011. The European School on Magnetism is now closely associated and held alternatively with JEMS conferences, the Joint European Magnetic Symposia.

Like previous editions of ESM, the 2011 School aims at providing a thorough insight in Magnetism based on a broad series of fundamental lectures, while proposing the latest insights in today's Magnetism with lectures focusing on a special topic. The topic chosen for the 2011 School is: "Time-dependent phenomena in magnetism". The aspects covered during the School will be: basic concepts, exchange interactions, magnetic ordering, coupling with the lattice, temperature effects, slow dynamics, precessional dynamics, ultra-fast dynamics, relevant experimental techniques.

The School is addressed mainly to PhD students and post-docs, both experimentalists and theoreticians. It will consist of approximately 40 hours of lectures, plus many practicals, open questions sessions (5-10h), and free access to a Library on Magnetism. More details may be found on the web site: http://esm.neel.cnrs.fr/2011.

VIBRATING LIQUIDS IN SPACE

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* DOI: 10.1051/epn/2010601

Natural convection is generated by buoyancy or capillary forces, but other forms of flows are possible when fluids are exposed to external vibration. Is it possible to mix liquids by shaking a completely filled container? An experiment is looking for answers on board the International Space Station

▲ The International Space Station as seen from the space shuttle Endeavour during the return flight of the STS-130 mission (February 2010) that brought to ground the hard disks with images and data from the IVIDIL experiment (credits: NASA).

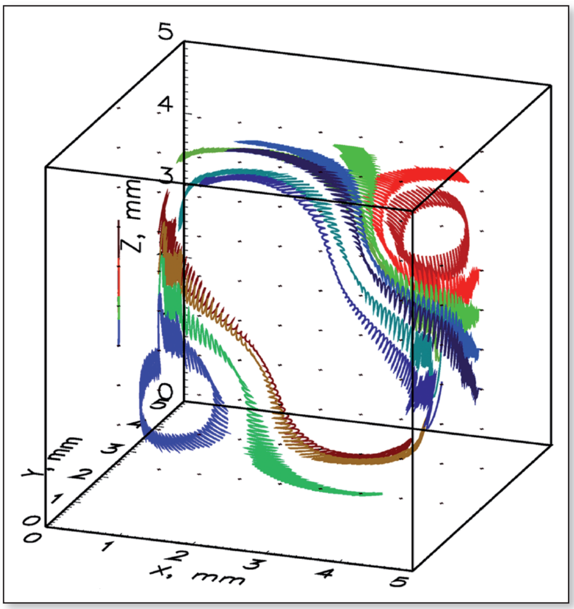
Everybody is familiar with the action of gravity on a fluid where density gradients are present due to heating or compositional difference. Due to buoyancy, the denser portions sink to the bottom of the container, pushing away the lighter ones. As a result, convection sets in, transporting heat and mass. In weightlessness conditions, this driving force is absent but inertia exists as the tendency of a body to resist acceleration. When a container filled with liquid is subjected to high frequency vibrations, the fluid is not able to react due to inertia and this may create a flow. If the density is uniform, then the fluid moves as a solid body. However, when density gradient is present, also inertia will not be uniform, resulting in convective motion. Obviously, there is analogy between gravity-induced and inertia-driven convection, as a result of the Einstein equivalence principle, although the second one is almost unknown. What would be the impact of vibration on dispersion by molecular diffusion and heat transfer without buoyancy?

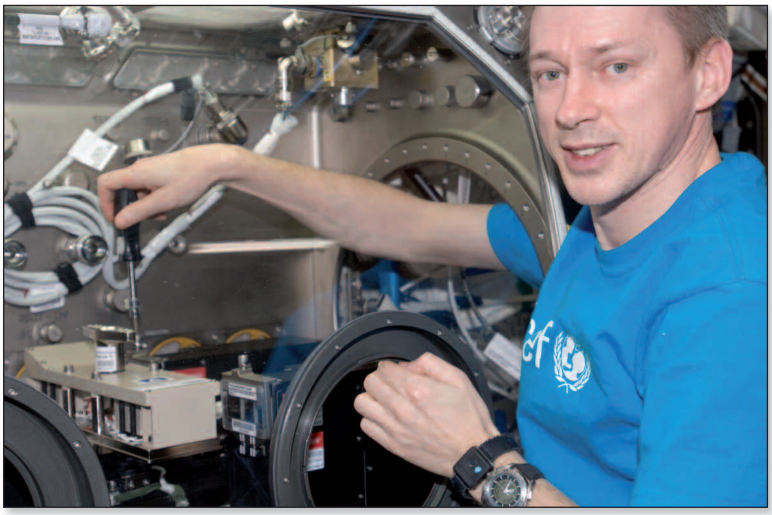
Vibration-induced convection

More than 30 years ago, Gershuni and Zhukhovitskii predicted that the application of controlled, high-frequency vibrations to a fluid system with macroscopic density gradients would give rise to flows across the sample [1]. Density gradients can be generated in a single-component fluid when a temperature difference is established across the container or in a fluid mixture where the concentration of different species is not homogeneous. Depending on the case to be studied, the effect is known as thermovibrational and solutovibrational convection, respectively. Naturally, the behaviour of a fluid system depends on the properties of the external vibrations. Here we restrict the discussion to a binary mixture subjected to *high* frequency vibrations. This applies to vibrations with a period similar to or smaller than the viscous (L^2/ν), thermal (L^2/χ) and mass diffusion (L^2/D) time, where L is a characteristic length of the container, ν the kinematic viscosity, χ the thermal diffusivity and D the mass diffusion coefficient. Under these rather general conditions, a mean flow with "slow" characteristic timescales develops, superimposed on a fast oscillating contribution that has the same frequency as the imposed external vibration. The difference between slow and fast oscillations is shown in Fig. 1, where simulated trajectories of a few particles are traced during the same time interval. Large diagonal and two corner rolls demonstrate the slow motion ("streaming") while high-frequency and small-amplitude oscillations correspond to "fast" motion. Vibration-induced mean flows have been extensively studied theoretically in single liquids and binary mixtures [2-4] (a comprehensive review is given in [2]). As in other forms of convective instabilities, the strength of vibration-induced convection is characterized by a hydrodynamic number. For the low vibrations that is the vibrational analogue of the Rayleigh number for buoyant convection, where the gravity is replaced by a vibration acceleration proportional to $A\omega^2$, A and ω being the amplitude and frequency of vibration, respectively. However, for the case of interest, *i.e.*, high-frequency vibrations, the analogue dimensionless number has a more sophisticated origin and follows an averaging approach [1-6]. It was suggested that it should be called the Gershuni number [5-7] to mark his significant contribution to the theory of thermovibrational convection, $Gs=(A\omega\beta_T\Delta TL)^2/2\nu\chi$ (β_T, ΔT, L, ν, χ being the thermal expansion coefficient, temperature difference, sample thickness, kinematic viscosity and thermal diffusivity, respectively).

Notwithstanding the fact that vibrational convection is fairly well understood in numerical and theoretical studies, no experimental evidence has been made available until very recently [5,6] due to the fact that buoyancy–induced flows are usually dominant over vibration-induced ones, therefore preventing their observation. As such, vibrational convection would become detectable in a reduced gravity environment, where buoyancy forces are "switched off" and the only forces acting on the fluid are the ones induced by the external forcing.

▼ **FIG. 1:** Fast and slow motion generated by vibrations. Trajectories of different fluid particles are shown by different colours. The small amplitude oscillations (fast) correspond to external frequency and the big roll is "slow" convective motion.



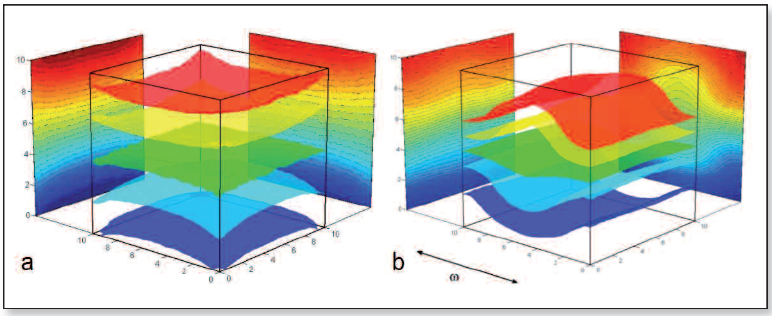


▲ **FIG. 2:** ESA astronaut Frank DeWinne, working with the IVIDIL experiment on the ISS.

The IVIDIL experiment

The study of vibration-induced convection is not just a purely academic problem for the advancement of our understating of hydrodynamic instabilities. There is a unique environment where this phenomenon may have tangible effects: the Columbus laboratory on board the International Space Station. There, slowly but steadily, experiments in fluid physics and material science are being performed since its activation in 2008. A few of them are dedicated to the measurement of (thermal)diffusion coefficients of multi-component liquid mixtures and metallic melts that are impossible to determine with a comparable precision in a normal gravity environment. In order to obtain an accurate measurement, macroscopic flows must be absent from the sample volume to avoid distorting the diffusive fronts. But while buoyancy is negligible, external vibrations, or g-jitter, are always present and may give rise to convective currents therefore affecting the measurements.

This is the main motivation behind IVIDIL (Influence of Vibration in Diffusion in Liquids), a project proposed to the European Space Agency (ESA) in 2000 by an international team including the Microgravity Research Centre of ULB (Brussels, Belgium), the Institute of Continuous Media Mechanics UB RAS (Perm, Russia) and Ryerson University (Toronto, Canada) and coordinated by the Brussels team. The project proposes to study the influence of vibrations on the measurement of diffusion and Soret (or thermal diffusion) coefficients in well known two-component mixtures by monitoring the temperature and concentration fields during diffusion.



▲ **FIG. 3:** 3D "tomography" of concentration field and its cross-section in two perpendicular directions at the central part in case of no **(a)**, and weak (Gs = 800) vibration **(b)**. 3D surfaces of iso-concentration are shown by different colours.

After several years of preparatory activities, the project culminated in 2009 with the performance of a three months experiment on board the ISS.

During each experimental run, a temperature difference is established across the cell, to achieve a separation of components as induced by the Soret (or thermal diffusion) effect. Then, the temperature difference is switched off, the cell is brought rapidly to isothermal conditions and the components get back to a homogeneous distribution. While the process takes place, the sample is shaken perpendicularly to the temperature gradient, with frequencies up to 2.8 Hz and amplitudes up to 68 mm. Part of the images acquired in the many runs performed were transmitted to ground and monitored by the different teams involved.

A sophisticated post-processing of interferograms allowed the quantitative observation of (thermal)diffusion processes as well as transient and steady state vibrational convection. Preliminary analysis has provided valuable insights into the formation and evolution of the concentration field with and without the action of vibrations. The central parts in plots of Fig. 3 show 3D surfaces of iso-concentration after 12h from the beginning of the experiment. Side graphs show central cross-sections of concentration field in two perpendicular directions (not near the walls). In the absence of external vibration the concentration field follows the structure of the temperature field (Fig. 3a). As experiments are never "ideal", the temperature field in IVIDIL is not perfectly linear approaching the corner regions, even though this "non-ideality" does not provoke convection in weightlessness. Hence, there is no motion in the system and 3D iso-surfaces are almost parallel, their shape resembling the roof of a "pagoda".

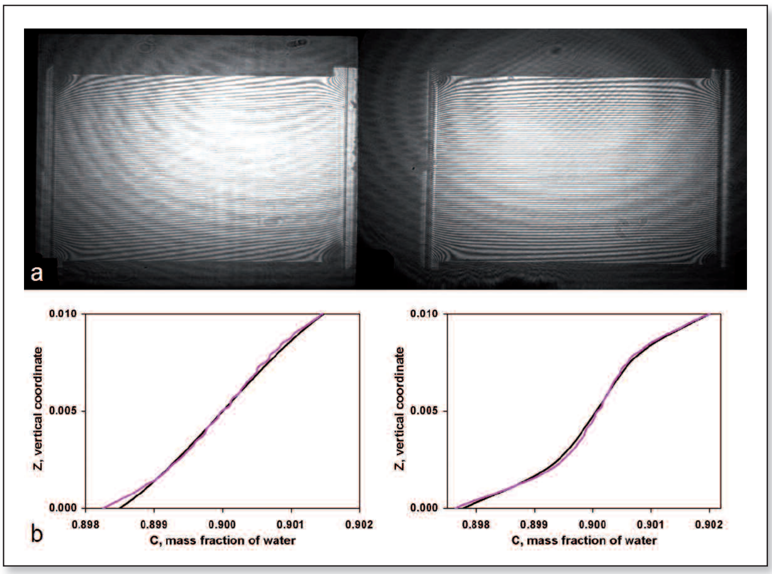
The situation is very different in the presence of vibrations: iso-surfaces are twisted by the flow as shown in Fig. 3b. The concentration field in the direction perpendicular to vibrations (graph of projections on the right side) gives an idea about the flow structure: four vortices are formed somewhat similar to those shown in Fig. 1 and is similar to a convective roll as observed in thermal convection. The increase of the vibrational energy, *i.e.* Gershuni number, will lead to more sophisticated flow patterns.

The 3D pictures in Fig. 3 were created on the basis of raw interferogram images obtained on the ISS that are shown in Fig. 4a. Besides the qualitative data, the accuracy of the experiment has also allowed quantitative data to be obtained, which are presented in Fig. 4b. Experimental data have been compared with numerical predictions, where concentration profiles along the temperature gradient in the middle of the cell (along central vertical line in 3D pictures in Fig.3) are presented.

The concentration profile in the absence of vibration (Fig. 4b) is linear and in excellent agreement with numerical predictions. This suggests that g-jitter did not affect diffusion at the present level of accuracy. However, high-frequency imposed vibrations do affect the mass transfer. The concentration profiles in the case of relatively weak forcing (f=2Hz, A=44mm, Gs=800) deviate from the linear profile due to the flow as shown in Fig. 4b on the right plot.

While the analysis of the full set of data received from space is ongoing, it is believed that IVIDIL will shed light on the complex mechanisms behind vibration-induced convection, and will provide useful insight on how to control fluids in space to support future physical and life science experiments. ■

▼ **FIG. 4:** **(a)** Typical interferograms of two perpendicular views of the cell. **(b)** Experimental (pink) and numerical (black) concentration profiles in the middle of the cell for water (90%) - isopropanol (10%) mixture with negative Soret coefficient (t=12h).



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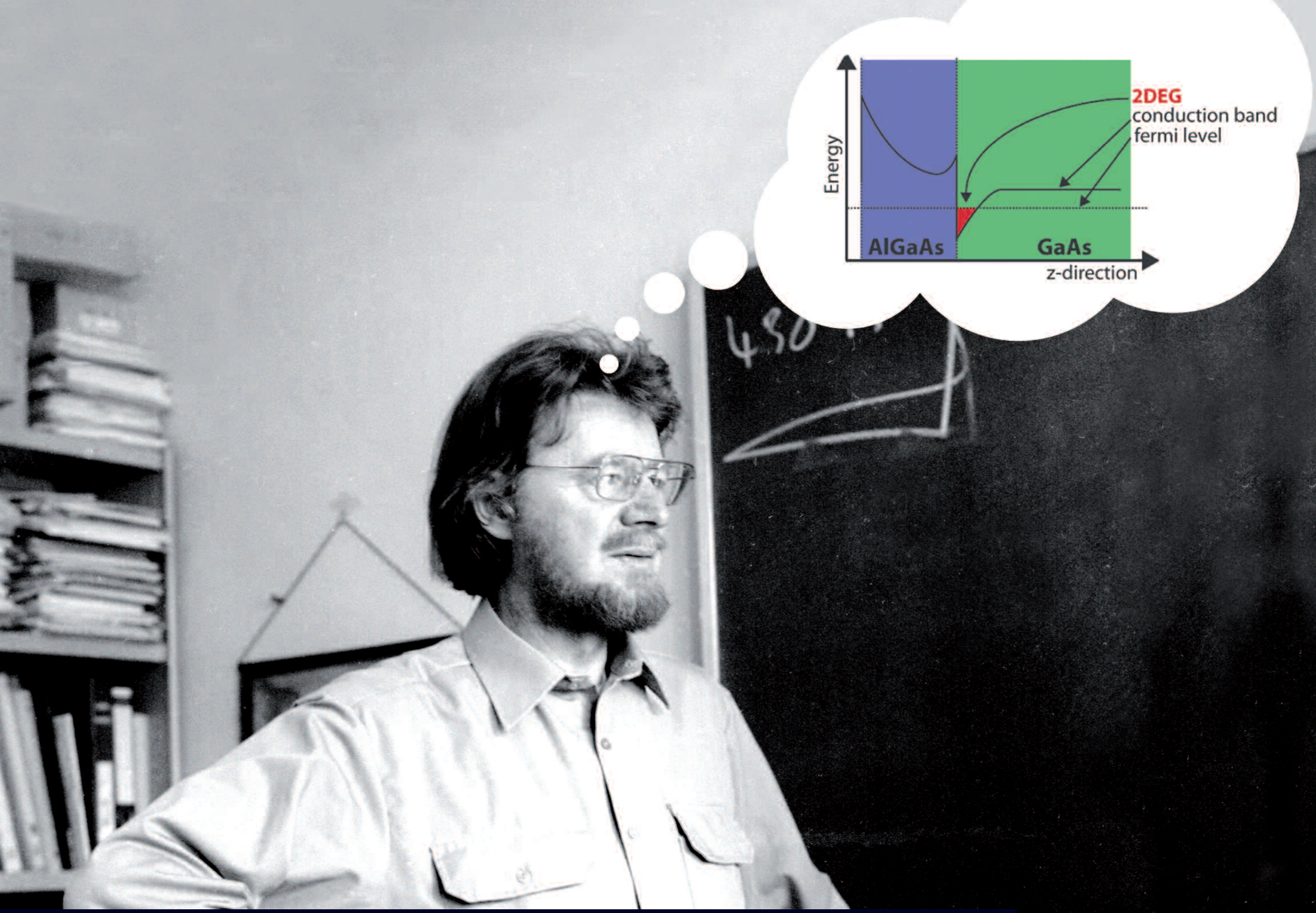

QUANTUM ENTANGLEMENT AND LOCALITY

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Can a measurement at location A depend on events taking place at a distant location B, too far away for the information to be transmitted between the two? It does seem too mysterious to be true. Even Einstein did not believe so. But experiments seem to prove him wrong.

It is well-known that until the end of his life Einstein was dissatisfied with quantum mechanics as a fundamental theory [1]. He strongly believed that the real world should consist of "systems" (particles, fields) that possess objective properties, *i.e.*, properties that do not depend on measurements by external observers. A second essential aspect of these objective properties is that the outcome of a measurement at location A cannot depend on events taking place at another location B, if B is sufficiently far away from A that information about the event at B travelling at the speed of light cannot possibly reach A before the measurement at A has been performed. Theories satisfying both of these criteria are called 'local' and 'realistic'. Quantum mechanics, in contrast with earlier developed classical theories, does not satisfy either of these criteria: properties of a quantum-mechanical system do depend on the experimental conditions under which they are measured, and a measurement at A can be influenced *instantaneously* by an event happening at B via the mechanism called entanglement (see

▲John Bell thinking - ahead of his time - about Bell tests with electrons in nanomaterials box). Einstein believed quantum mechanics to be mathematically consistent, but insisted that in spite of this it should be a local realistic theory. Based on this conviction, he came to the conclusion that present-day quantum mechanics is an incomplete theory, and that there should be a deeper underlying theoretical framework that does enable us to establish an objective description of quantum-mechanical phenomena.

In 1935 Einstein, together with Boris Podolsky and Nathan Rosen, wrote a by now famous article in which

Entanglement and Bell's inequality

An entangled state of two or more particles is characterized by the fact that it is not possible to write the state of the full wavefunction as a product of the wavefunctions of the individual particles. A prototype entangled state is the spin singlet $|\psi\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$, which we use here to illustrate the locality paradox as mentioned in the main text. This paradox consists of the following: image two experimentalists in two distant laboratories who each receive one of the two spins in the singlet state. If both of them measure the direction of their spin using identically positioned polarizers, they will always find opposite polarizations, *i.e.* the outcomes of the measurements are one hundred percent correlated with one another. Moreover, this correlation is formed instantaneously and without communication between the two experimentalists and thus it appears as if information has been exchanged at a speed faster than the speed of light. The solution of this apparent paradox lies in the fact that the entanglement of the two spins already existed prior to the measurements. In addition to traditional entangled states such as the spin singlet, more "exotic" types of entanglement exist such as bound entanglement (see the article following this one by Horodecki *et al.*).

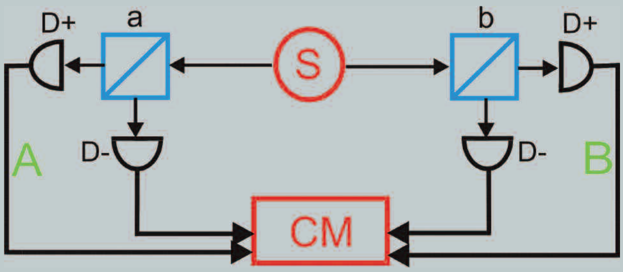
To illustrate Bell's inequality, we use the formulation given by Clauser, Horne, Shimony and Holt [3] which was used in the photon experiment performed by Aspect, and also forms the basis of the proposals for a Bell test with electrons. Consider a source that emits pairs of correlated particles – photons or spin-1/2 particles – such that one particle is sent to polarizer a and the other to polarizer b, see Figure 1. The polarizers measure the polarization (or spin) components of the particles in a chosen direction and yield outcome + or -. Depending on this outcome the particle is then registered by detector D+ or D– . We consider the situation in which 4 settings of the polarizers are used, namely φ_A and φ_A' for polarizer a and φ_B en φ_B' for polarizer b. In a local realistic description both particles have fixed intrinsic polarisations for each of the 4 settings. Each pair of particles can then be symbolically described by the combination $(\sigma_A\sigma_{A'}\sigma_B\sigma_{B'};\tau_A\tau_{A'}\tau_B\,\tau_{B'})$, where $\sigma_A = \pm$ and $\tau_A = \pm$ denote the outcomes of the polarisation measurements of, respectively, particle 1 and particle 2 in the direction φ_A, etc. Assuming the particles to be in the singlet state (for other entangled states a similar reasoning can be made) we have that $\tau_X = -\sigma_X$, for X=A, A′, B and B′. Each pair of particles is then fully characterized by the combination $(\sigma_A\sigma_{A'}\sigma_B\sigma_{B'})$. Let $f(\sigma_A\sigma_{A'}\sigma_B\sigma_{B'})$ be the fraction of the total amount of pairs produced by the source which yield outcome $(\sigma_A\sigma_{A'}\sigma_B\sigma_{B'})$. We now consider the parameter S, defined as

$$S = |E(\varphi_A,\varphi_B) - (\varphi_A,\varphi_{B'}) + (\varphi_{A'},\varphi_B) + (\varphi_{A'},\varphi_{B'})|, \tag{1}$$

in which

$$E(\phi_A,\phi_B) \equiv \sum_{\sigma A',\sigma B'} [f(+,\sigma_{A'},-,\sigma_{B'}) - f(+,\sigma_{A'},+,\sigma_{B'}) - f(+,\sigma_{A'},-,\sigma_{B'}) - f(-,\sigma_{A'},-,\sigma_{B'}) + f(-,\sigma_{A'},+,\sigma_{B'}) \tag{2}$$

By substituting (2) in (1) and using that $\sum_{\sigma A,\sigma A',\sigma B,\sigma B'} f(\sigma_A,\sigma_{A'},\sigma_B,\sigma_{B'}) = 1$ it follows directly that $S \leq 2$. This is Bell's inequality.



▲ **FIG. 1: Schematic illustration of a Bell test: a source S produces pairs of correlated particles, *e.g.*, photons, which leave the source one by one and in opposite directions. The polarisation of particle 1 is measured by polarizer a in the direction φ_A and, depending on the outcome, the particle is registered by detector D+ or D-. Similarly, the polarisation of particle 2 is measured by polarizer b in the direction φ_B. Coincidences are then counted by the coincidence detector CM. Source: Sketch of a two-channel Bell test by Caroline H Thompson.**

they advocated this opinion and explained how the notion of objective properties is incompatible with the assumption of quantum mechanics being a complete theory [2]. This 'EPR' paper launched a heavy debate on the question whether quantum mechanics could be modified into a local realistic theory.

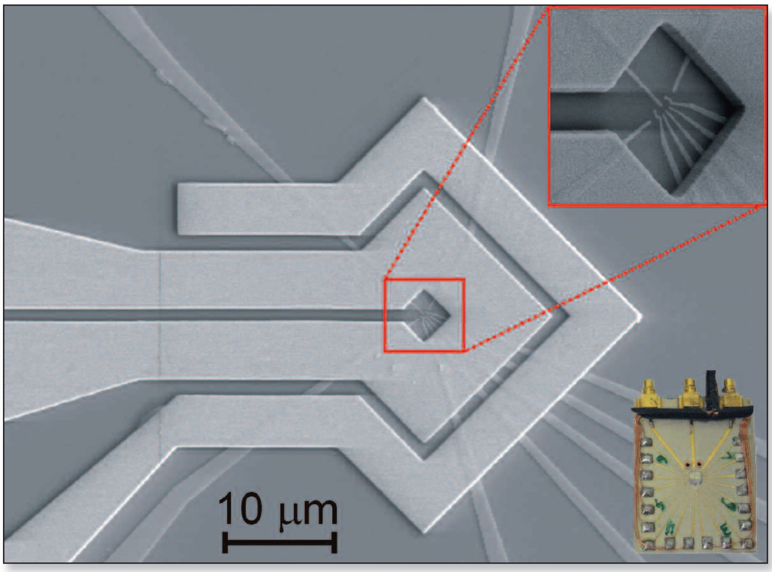
This debate got an interesting turn in 1964, nearly ten years after Einstein's death. In that year John Bell published a quantitative criterion, now known as Bell's inequality, which every local realistic theory should satisfy (see box). This inequality opened the way for experiments that can be used to prove the existence of entanglement and ultimately test whether quantum mechanics is complete or not.

Bell test with photons

The first experimental tests of Bell's inequality were performed in the 1970s using pairs of photons in a polarization-entangled state. Nearly all of them led to results violating Bell's inequality. In 1982 Alain Aspect and his co-workers in Paris succeeded in violating Bell's inequality by many orders of magnitude. Their experimental set-up is schematically depicted in Fig. 1 [4]. In spite of the fact that these results were in clear agreement with predictions of quantum mechanics, they do not exclude the possibility of a local realistic theory for two reasons. These are known as the detection and locality "loopholes".

The first loophole refers to the technical problem that in practice not all pairs emitted by the source are detected, which is an essential assumption in the derivation of Bell's inequality (see box). In Bell experiments, therefore, great care is taken to ensure that the detected pairs form an accurate reflection of all pairs emitted. Nevertheless, in principle the possibility remains that the latter is not the case, and that the results would satisfy Bell's inequality if all particles were detected. Bell's own opinion on this issue was [5]: *"Although there is an escape route there, it is hard for me to believe that quantum mechanics works so nicely for inefficient practical set-ups, and is yet going to fail badly when sufficient refinements are made. Of more importance, in my opinion, is the complete absence of the vital time factor in existing experiments."*

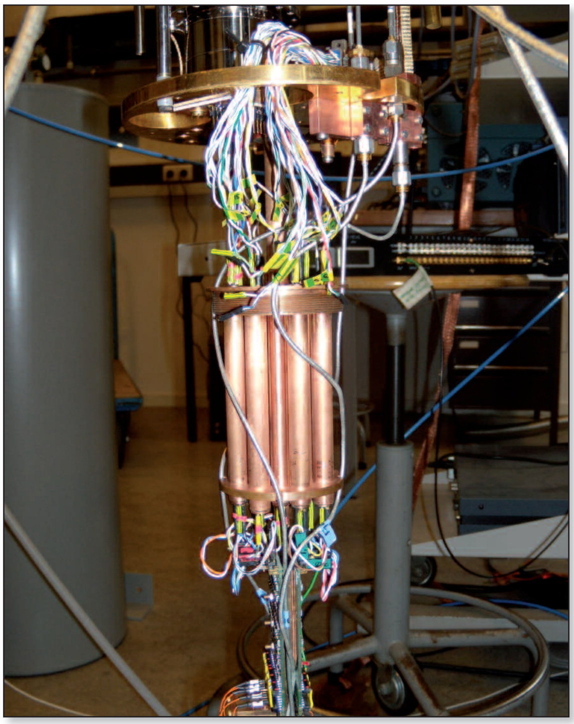
The last sentence refers to the other loophole, the locality one, which says that it is essential for a reliable Bell test that the measurements at A and B are completely independent and, in particular, that the polarizers should be set well after the moment that the particles left the source. Only in this way it is possible to test for instantaneous long-distance influence among the particles, that could not have been communicated at the speed of light. In the meantime, some experiments have been performed using polarizers that were controlled by random generators on timescales that are short compared to the travel time of photons [6], and also their outcomes are in disagreement with Bell's inequality.



▲ **FIG. 2: Schematic illustration of a double quantum dot (expanded area) defined by nanoscale metal top gates in a two-dimensional electron gas (2DEG) and covered by a microscale loop antenna. A 2DEG is a two-dimensional layer in a semiconductor structure in which electrons can move freely, *i.e.* without interactions, while preserving the phase properties of their wavefunction across longer distances (typically a few tens of μm). The dots are formed when an electric voltage is applied across the metal top gates) which pushes the electrons underneath the gates away. In this way, local islands of electrons surrounded by high potential barriers (the gates) are formed in the 2DEG. The inset shows a photograph of the sample holder. (Source: www.nano.physik.uni-muenchen.de)**

Bell test with electrons?

Apart from Bell measurements with photons, also experiments with entangled pairs of protons, kaons, neutrons, cold atoms and photon-atom pairs have been performed [7] - but not yet with electrons. The main reason for this lies in the difficulty to find or construct a source that produces isolated entangled electron pairs (due to the Coulomb interaction between electrons in solid-state structures) and to preserve the coherence of these pairs, i.e., the phase properties of their quantum state, over distances longer than a few micrometers [8]. Nevertheless, hope exists that proof-of-principle Bell experiments will become possible in the near future due to recent experimental developments in the field of solid-state nanophysics, in particular the progress that is currently being made on coherent manipulation of individual electrons in semiconducting nanostructures [9]. As a result, during the last few years several theoretical proposals have been put forward for testing Bell's inequality in solid-state nanosystems [10-12]. These are for example based on the idea of using a superconductor [10] or tunnel barriers in a two-dimensional electron gas (2DEG, see Fig. 2) [11] as a source of entangled electron pairs. In these schemes the idea is to test Bell's inequality by measuring current-current correlations (noise). This is different from the optical experiments that have been performed, in which photons are detected one by one and thus counted directly. Direct counting of electrons according to their spin direction is more difficult to realize, but recently a technique has been developed to achieve this [13]. ▮▮▮



▶ **FIG. 3:** Top view of a cryostat in which low-temperature experiments on quantum dots are done. Source: Quantum Transport group at Delft University of Technology. [Courtesy Lars Schreiber, TU Delft]

This opens the way for a Bell experiment with electrons, analogous to the optical one by Aspect. The basic idea [12] is to use spin-entangled electron pairs in quantum dots, see Fig. 2. Quantum dots are isolated islands of charge in a 2DEG semiconductor structure. Electrons can be transferred one by one onto the islands by manipulating externally controllable gates. Two islands adjacent to each other – a so-called double quantum dot – containing two electrons form the source of entangled electron pairs in this electronic Aspect scheme. To begin with, the gate in between the dots is open and the electrons naturally form a spin-singlet state, which is the ground-state of this system. Then this gate is closed, leaving one electron on each dot (due to Coulomb interaction) while their entanglement remains intact. After opening the two "exit gates" (Fig. 2) the electrons leave the dots and travel through electronic quantum channels to the "polarizers". These polarizers also consist of quantum dots, in which the two electrons are subsequently confined. By switching on a local magnetic field in each dot, the spin of the electrons is coherently rotated via an electron-spin resonance process. The time during which the magnetic field is applied determines the angle of rotation of the spin. Finally, the spin of each electron is measured upon leaving the dots [13]. By repeating this experiment for many electron pairs the probability of detection of each of the four possible outcomes (both spins up, spin 1 up and spin 2 down, etc.) is determined and this is used to test Bell's inequality.

Loopholes

How about the loopholes in this electronic Bell scheme? In principle, only by detecting every entangled pair the detection loophole can be firmly closed. Until more sensitive detectors become available we thus depend, as in the photon experiments, on the assumption that the pairs detected form an accurate reflection of all pairs emitted. A more serious problem is the fact that the time required for rotating the spins is much longer than the time required for the electrons to travel from the double quantum dot (the source) to the single quantum dots (the polarizers). This can not be remedied by increasing the distance between the dots, since in that case the travel time of the electrons is so long that the chances of decoherence of their (entangled) quantum state would become rather large. Faster spin rotation times, on which steady progress is being made, would enable the closing of this locality loophole. But the first goal in solid-state Bell nanophyiscs is more modest and does not require closing of the loopholes: to prove that the detected electron pairs were entangled. This has not yet been achieved and will be an important step forward in the field of solid-state quantum information processing. ■

About the author

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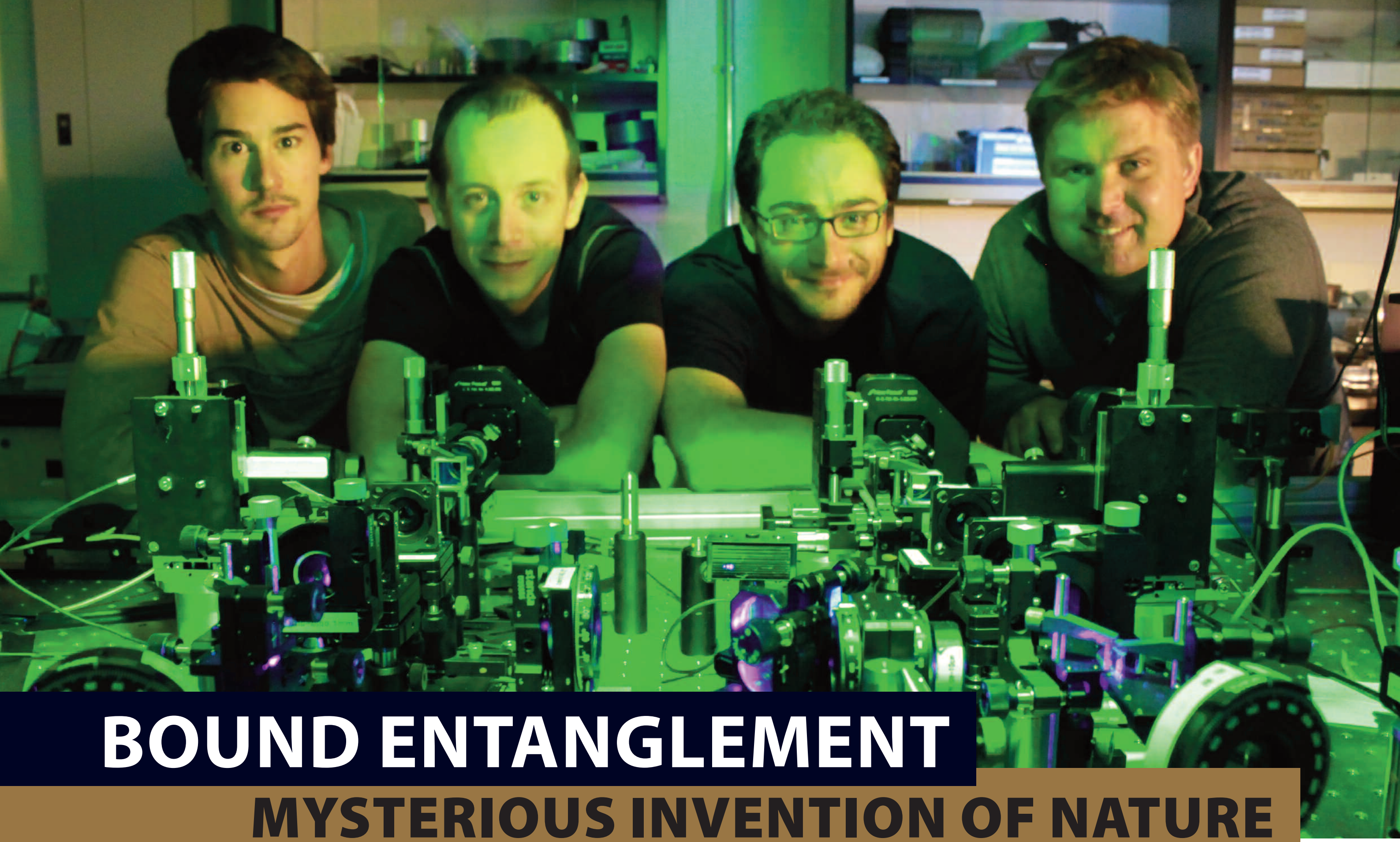

BOUND ENTANGLEMENT
MYSTERIOUS INVENTION OF NATURE

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* DOI: 10.1051/epn/2010603

When in 1998 the team of researchers of the Institute of Theoretical Physics and Astrophysics of the University of Gdańsk predicted the existence of bound entanglement, there was only one more thing to do: to believe that sooner or later this peculiar phenomenon would be confirmed empirically in laboratory conditions.

Eleven years later, on 23rd August 2009, *Nature Physics* [1] reported that the researchers of a laboratory in Stockholm had created a four-qubit bound entangled state. Another eight months later, on 30th April, another team from the laboratory in Dortmund reported the creation of pseudo-bound entanglement [2]. When that paper was in preparation, a team of researchers from Waterloo (see Fig.1) announced [3] that they had managed to experimentally create a genuine bound entangled state. At the same time the Innsbruck group presented an experiment implementing bound entanglement with ions [4]. The exciting course of these events already shows that experimental, unrecoverable imprisoning of quantum correlations, even in the simplest (four-qubit) arrangement, is no small challenge.

At the current stage, full understanding of bound entanglement – "a mysterious invention of nature" [5] – may be no more than an illusion. Nevertheless, it is interesting to follow the paths that led to that invention in a foggy bush of quantum formalism, in order properly to appreciate the efforts and inventiveness of experimentalists.

On the tracks of bound entanglement

Entanglement is "the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought" [6]. Indeed, let us look for instance at the singlet state $|\psi^0_{AB}\rangle = 1/\sqrt{2}\,|0\rangle|1\rangle - 1/\sqrt{2}\,|1\rangle|0\rangle$ of a pair of polarization-entangled photons (the symbols 0 and 1 designate correspondingly the vertical (V) and horizontal (H) polarizations). It is a pure state, *i.e.*, it represents our maximum available knowledge about the arrangement of two polarization-entangled photons. As we know, the quantum formalism allows the existence of mixed states, which represent incomplete knowledge. The paradox consists of the fact that the whole system is in the pure state while its subsystems are in the maximum mixed states. In other words, if partners in two distant laboratories measure the polarisations of both photons using identically positioned polarisors, they will always receive opposite polarizations (Fig. 2a). Moreover, the results of these measurements cannot be known to anyone prior to measurement (in

▲ FIG. 1: Waterloo experiment team. Left to right Jonathan Lavoie, Rainer Kaltenbaek, Marco Piani, Kevin Resch

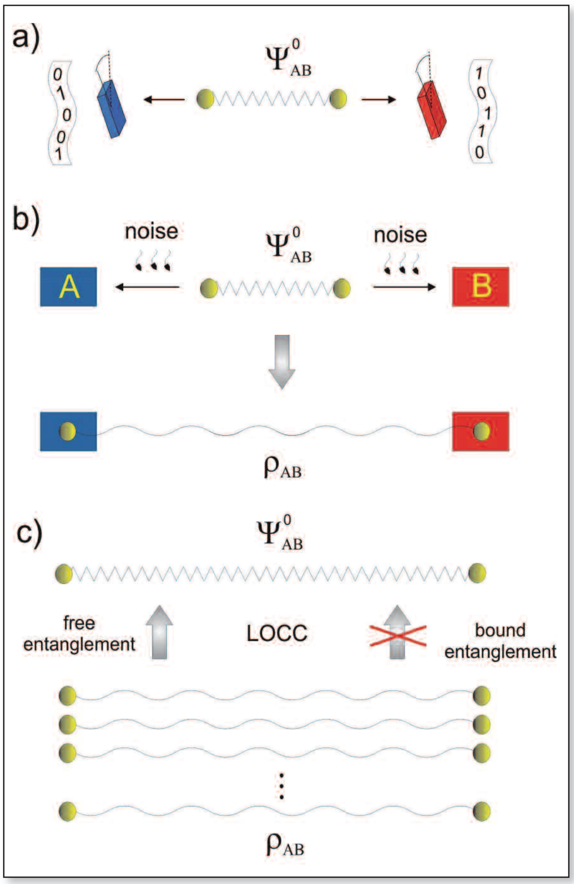


FIG. 2: **(a)** Pure entanglement produces perfect correlations. **(b)** The environment pollutes pure entanglement. **(c)** For distillable states, the reverse process is possible, while from bound entangled states one cannot obtain the pure entanglement back.

contrast to common, classical correlations, *e.g.*, momenta of slivers of an exploded projectile). On the other hand, the polarizations of photons independently measured by each partner are completely chaotic. Thus there is complete chaos in both subsystems, while the whole system is in perfect order. This unusual property of the state does not correspond to any situation in the classic world [7].

In an ideal situation, when quantum objects are entangled to the maximum extent, we can determine the state of one of them with certainty by measuring the state of the other. This, however, is only true for pure states which are not correlated with the rest of the world, that is, when we have "fuel" of the highest quality. In real situations, however, a system of entangled particles always interacts with its environment, which results in a situation of noised entanglement. This in turn results in a weakened quantum correlation. Formally, this means that the system of entangled particles passes into a mixed state ρ_{AB} (see Fig 2b), which can be interpreted as some information about system having leaked into the environment, resulting in degradation of entanglement. Thus, quite naturally, the following fundamental questions arise: a) How can we verify theoretically whether a given state (described on a sheet of paper) is entangled? b) Is direct detection of entanglement possible in a laboratory? c) Is it possible to reverse the process of degradation of quantum entanglement somehow?

Research into these issues was independently undertaken in the 1990s in several research centres [7]. While working on the first two issues in Gdańsk, we were astonished by the work of Asher Peres [8], who proposed an extremely strong criterion of entanglement, based on the so-called operation of partial transposition. Such an operation is carried out on one (A or B) subsystem of the state of a compound AB system. If the state subject to such an operation does not "survive" it, in the sense that it ceases to be positive, losing its probabilistic interpretation, it means that it was entangled. Mathematically speaking it means that its partially transposed density matrix has at least one negative eigenvalue.

Inspired by Peres' result we managed to prove [9] that a two-system state ρ_{AB} is entangled if and only if there is such an observable quantity W, that its average value in this state is negative, while it is always non-negative for all un-entangled states. This was the cornerstone of the method of detection of entanglement in laboratory conditions developed later, based on witnesses of entanglement [7]. While preparing a certain state in a laboratory we can always find a witness of entanglement corresponding to it, and then, by measuring it, verify whether or not the prepared state was entangled. The ceaseless popularity of detection of entanglement based on the method of witness of entanglement results from its simplicity and economy. To determine the presence of entanglement it suffices to measure only one or two observables (*e.g.*, the value of the spin or the polarization).

In spite of that, we were not completely satisfied. We did not know what happens when the system "survives" the operation of partial transposition. From the work of Peres it was possible to infer that if the state was un-entangled, then after such an operation it would still be un-entangled. But are there states in nature which are entangled and nevertheless have a positive partial transposition? Fortunately we managed to prove the existence of those strange states [9]. Our work has raised considerable interest among mathematicians, who considered related issues, expressed in a different language, as long ago as the 1970s. Of course physicists immediately expressed their wish to know what such states might look like.

Anna Sanpera (Barcelona) turned to Peres with this question, and he redirected it to our team. One of us (P. Horodecki) constructed the first entangled states with positive partial transposition [10]. The result raised interest at a conference in Torino (Italy) (1997), but in view of the lack of physical reference, the existence of such states was perceived as a mathematical peculiarity only. It would have remained such a peculiarity, if on the other side of the Atlantic, Bennett and his collaborators had not worked on the issue of (c): How to reverse the process of degradation of entanglement.

Their work [11] , published in 1996, had a key role to play in the theory of manipulation of entanglement. They introduced a natural class of operations of manipulation of entanglement by experimentalists located in remote laboratories. The experimentalists can only carry out any local operations on their entanglend particles and communicate via a classical communication such as a telephone (local operations and classic communication (LOCC)). On the basis of this concept they proposed a protocol of *distillation* of noisy entanglement: two partners in distant laboratories share n copies of the ρ_{AB} state, which contains noisy entanglement. Carrying out in their laboratories local operations on the subsystems of the shared state and using classic communications channels (*e.g.* a telephone) they can obtain the singlet state ψ^0_{AB}, which contains pure entanglement (Fig.2b). We then became interested in finding the answer to the question: Has the process of entanglement distillation a universal character? In other words: Can all the states in nature be distilled thanks to the application of the LOCC operations?

We managed quite quickly to demonstrate that all noisy entangled states of systems made of two qubits can be distilled. The results were very promising and there was a widespread belief that its generalisation would remain only a question of time. The idea that a purely mathematical operation of partial transposition without a clear physical interpretation could have anything in common with the "physical" protocol of distillation seemed absurd. However, when we considered more complicated systems, we obtained surprising results. Paradoxically, nature subject to a purely mathematical treatment revealed the physical peculiarity of entanglement: namely, that the environment may "pollute" the pure entanglement in such a way that it will not be possible to cleanse it with the help of LOCC (Fig.2c). Our conclusion was laconic: entangled states with positive partial transposition are LOCC undistillable [12]. This became known under the name of "bound entanglement".

This result astonished the physicists. It transpired that the structure of entanglement is not uniform! In nature there are at least two types of noisy entanglement: free, *i.e.* distillable entanglement and bound entanglement, which cannot be distilled with the help of the LOCC. In this way nature reveals the existence of a new type of quantum irreversibility which appears during the manipulation of entanglement. Namely to create bound entangled states by means of only local operations and classical communication, one has to have initially a certain amount of pure entanglement. However, using these operations, one cannot extract this pure entanglement back from the state.

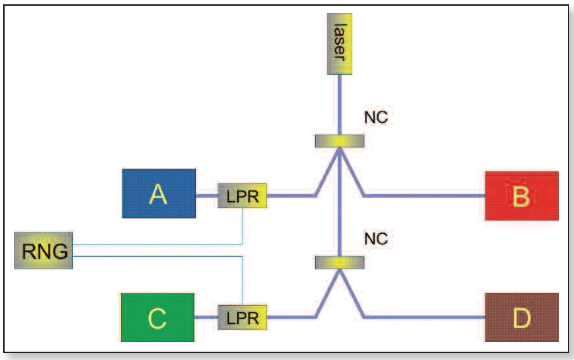
Bound entanglement in a laboratory

Since 1997 a number of states with bound entanglement have been constructed. One of the simplest and most elegant examples is Smolin's four-qubit state [13], which is an equal mixture of four Bell's states $|\psi^{0(1)}_{AB}\rangle = 1/\sqrt{2}\,|0\rangle|1\rangle \pm 1/\sqrt{2}\,|1\rangle|0\rangle$ and $|\psi^{2(3)}_{AB}\rangle = 1/\sqrt{2}\,|0\rangle|0\rangle \pm 1/\sqrt{2}\,|1\rangle|1\rangle$:

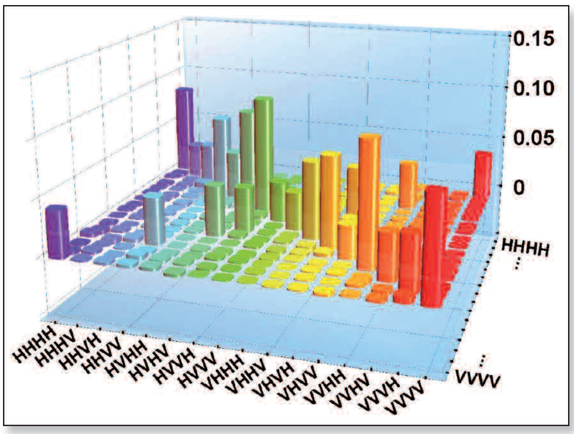
$$\rho_s = \frac{1}{4}\sum_{i=0}^{3}|\psi^i_{AB}\rangle\langle\psi^i_{AB}|\otimes|\psi^i_{CD}\rangle\langle\psi^i_{CD}|. \qquad (1)$$

Physically, the Smolin state can be interpreted in the following way: Partners A and B in distant laboratories share one of the four possible Bell states. Similarly, partners C and D share the same state. Each of those four Bell states appears with the probability of 1/4 and is unknown to the partners. Smolin demonstrated a specific property of this state: if four qubits are far from one another, it is not possible to distil the entanglement between any of them. If, however, only two qubits are in the same laboratory, it is possible to create a pure entanglement in the form of singlets between the two remaining qubits A and B with the help of the LOCC operations. Thus the state of Smolin contains bound entanglement. Its simplicity and high symmetry in relation to the exchange of qubits attracted the attention of experimentalists as an optimal candidate for quantum - optical implementation. In the experiments of the Stockholm and Waterloo teams the physical qubits are represented by polarized photons (see Fig. 3).

Experimentalists can hope that they will be able to create a four photon bound entangled Smolin state (2), but how can they subsequently verify it? As we already know, the state has to meet two criteria, *i.e.* it has to be entangled and not distillable. The first feature may be achieved by measuring an appropriate entanglement witness. If the measurement returns a negative average value,



◄ **FIG. 3:** The Smolin state in the Waterloo experiment was prepared in the following way: two sources, nonlinear crystals (NC This symbol is not used in the Figure) pumped by a single laser, generate two-photon pairs in the state $|\psi^i_{AB}\rangle$ encoded in the polarization of photons, where H and V correspond to the horizontal and vertical polarization, respectively. Then, according to the prescription of Smolin, the initial state $|\psi^i_{AB}\rangle|\psi^i_{CD}\rangle$ should randomly and with equal weight transform into the remaining states of the Bell base and be disseminated among the analysers A, B, C and D symbolising distant laboratories. The authors managed to accomplish this by applying the liquid crystal phase retarders (LPR) in each of the two sources. They were controlled by a computer using a pseudo-random number generator.



◄ **FIG. 4:** Tomographic picture of Smolin's state prepared by the Waterloo team. (The figure has been reprinted from [3]) it means that the prepared state was entangled. Secondly, the state, in order to be nondistillable, has to have a positive partial transposition. This may be checked by making a full tomography of the state (see Fig. 4). It appears that meeting the second criterion is quite difficult in the case of the state suggested by Smolin due to the fact that the property of positive partial transposition is extremely sensitive to imprecision in preparing the state and low data statistics. In the pioneering Stockholm experiment [1] under conditions of low ("natural") noise the minimum proper value was negative *i.e.* -0.02 ± 0.02. In this sense the demonstration of bound entanglement is not fully convincing. The Waterloo team (Fig. 1) then realised that by adding a large (nearly 50%) amount of white noise to the original state of Smolin the bound entanglement became much more robust. In the experiment, the observed average of the witness was -0.159 ± 0.008, while the smallest eigenvalue of the partially transposed state was positive: 0.0069 ± 0.0008.

In parallel with Waterloo experiment an independent realization of bound entanglement was carried out in Innsbruck [4] with ions. Their main advantage over the photonic experiments mentioned in the article is that the state is prepared unconditionally. Namely, in the Stockholm and Waterloo experiment, in gathering the statistics one must exclude some instances, *e.g.* when the photons didn't reach the detectors. Thus, in a sense, the experimenters get to know that they indeed prepared the valid state only after it is destroyed (*i.e.* after the photons are detected). This is called "post-selected" regime, and is common to almost all experiments with single photons. In contrast, in the Innsbruck experiment no such post-selection is applied.

Another ingenious experiment has independently been carried out in Dortmund [2]. A three-qubit pseudo-bound entanglement was created in a liquid using the method of Nuclear Magnetic Resonance. Using similar methods, *i.e.* the tomography and entanglement witnesses, the authors have shown that bound entanglement can exist in a laboratory.

The list of peculiarities and potential applications of bound entanglement is diverse and growing [7]. We already know that "bound entanglement is not a rare phenomenon" [15] since its presence was discovered in thermal spin systems [14,15]. At the same time, we are still far from complete understanding of the phenomenon of bound entanglement, which raises new experimental and theoretical challenges for the future.

► Gdańsk group. Left to right: Ryszard Horodecki, Michał Horodecki and Paweł Horodecki.

Note added

After completing this manuscript, further experiment realising bound entanglement has been announced by the Hannover group [J. DiGuglielmo *et al.*, http://arxiv.org/abs/1006.4651] with light in continuous variable regime. As in the Innsbruck experiment, no post-selection was applied. ■

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- Johannes Hevelius Scientific Award of the City of Gdansk
- Group Wojciech Rubinowicz Award granted by the Polish Physical Society

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▲ OPERA detector. Photo on permission of LNGS-INFN

THE APPEARANCE OF THE TAU-NEUTRINO

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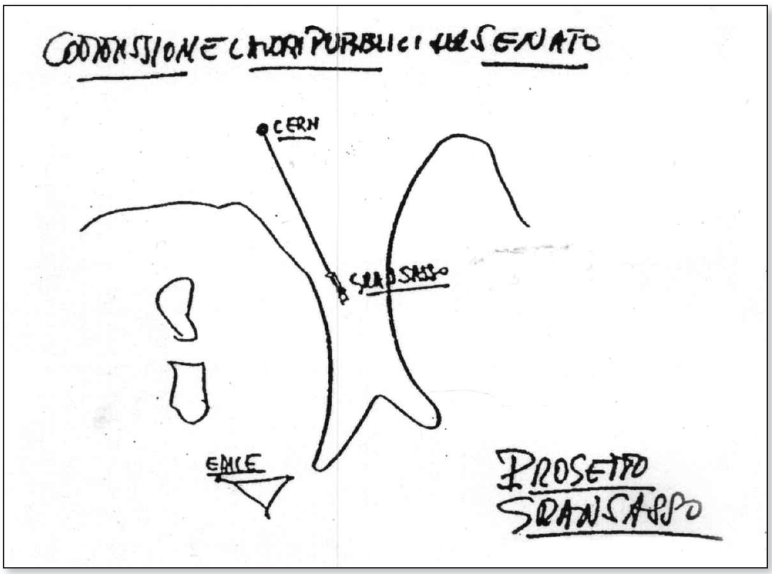
On August 22nd 2009 a very special event was recorded by the OPERA experiment at the INFN Gran Sasso Laboratory produced by a neutrino coming from CERN. Born as mu-neutrino, it had transformed into a tau-neutrino on its 730 km long route. This is a long-awaited achievement of an enterprise started 30 years ago.

Neutrinos change family

The spin ½ elementary particles come in three different groups, called families, of identical structure. Each family is made of two quarks, of charge +2/3 q and –1/3 q (q is the proton charge), and two leptons, one of charge $-q$ and one neutral. The neutral leptons are collectively called neutrinos, but are three different particles, distinguished by an additive quantum number called "lepton flavour". The electron (e^-) and the electron-neutrino (ν_e) have one unit of electronic flavour (−1 their antiparticles); the muon (μ^-) and the muon-neutrino (ν_μ) have one unit of muon-flavour, and similarly for the tau (τ^-) and the tau-neutrino (ν_τ).

The charged leptons are distinguished by their different masses (increasing with the family number) and lifetimes, neutrinos only by their lepton flavours, which are conserved in the interactions. Neutrinos are produced in states of definite flavour, as ν_e, ν_μ or ν_τ, each with an antiparticle of the same flavour, its antineutrino or e^+, μ^+ or τ^+, respectively. When a neutrino of a certain flavour interacts with a target producing a charged lepton, the latter always has its flavour; for example a ν_μ produces a μ^-, never an electron or a tau.

Experiments in underground laboratories have shown that neutrinos do not behave as assumed in the Standard Model (SM): they do change, "oscillate", between one flavour and another. The evidence has gradually grown in the last four decades, by studying the ν_es produced by the fusion reactions in the core of the Sun and the ν_μs indirectly produced by the cosmic rays collisions in the atmosphere.



▲ **FIG. 1: Geographical sketch of the neutrino beam from CERN to Gran Sasso by A. Zichichi (1979)**

Neutrino oscillations

Neutrino oscillations happen because neutrinos of definite flavour, ν_e, ν_μ and ν_τ, are not stationary states, *i.e.*, states of definite mass, but linear combinations of those. We call the latter ν_1, ν_2 and ν_3 and m_1, m_2 and m_3 their masses.

Oscillations phenomena are common in physics. Consider for example two identical pendulums, a and b, of mass m and length l weakly coupled by a spring of constant k. The system has two normal modes, obtained by defining its initial state. In each mode the two pendulums oscillate harmonically and synchronically with (proper) frequencies, say, ω_1 and ω_2. The first mode is obtained by letting them go from the same initial elongation with zero initial velocities. The squared frequency is $\omega_1^2=g/l$. In the initial state of the second mode the two elongations are equal and opposite and the velocities are zero. The squared frequency is $\omega_2^2=g/l+2k/m$. Considering for the moment a world with only two neutrinos, the analogues of the modes are ν_1 and ν_2 and the analogues of the frequencies are the masses m_1 and m_2.

The analogue of a neutrino of flavour a is the initial state with pendulum a abandoned with zero velocity at a certain initial elongation and pendulum b in its at rest position. Vice versa for flavour b. One observes that the motion does not have a definite frequency. Rather, the amplitude of the vibrations of a gradually decreases down to zero, while that of those of b increases up to a maximum. Then the evolution inverts. Hence, the energy "oscillates" periodically from a to b with a frequency ω_2-ω_1. In the quantum system the analogue of energy is the probability to observe the flavour, because both are proportional to the square of the amplitude. To observe the phenomenon one needs to leave a time long enough to allow for its development. In practice this means having the detector far enough from the source. Then there are two alternatives: to look for the disappearance of the initial flavour (looking at a) or for the appearance of the new one (looking at b).

However, there are *three* neutrinos. The analogue is a system of three coupled pendulums. Moreover, the pendulums may not be equal. Clearly the phenomenology becomes much richer.

In 1968 R. Davis [1] published his measurement, started in 1964, of the flux of neutrinos from the Sun with an experiment sensitive to ν_e. The flux was smaller, about 1/3, than the theoretical calculations by J. Bachall [2]. When the preliminary results became known, B. Pontecorvo [3] claimed that the disappearance might be due to neutrinos changing flavour through oscillation, a concept he had introduced in 1957. Further ν_e disappearance experiments, in different energy ranges, KAMIOKANDE [4] and Super KAMIOKANDE [5] in Japan, GALLEX/GNO [6] at Gran Sasso and SAGE [7] at Baksan, had established by 1998 that the Pontecorvo idea was right. The final proof came from the SNO [8] in Canada in 2002. All neutrino flavours can interact with nuclei producing a neutrino in the final state, instead of a charged lepton. The final neutrino cannot be detected, but the effect on the nucleus can. This was done by SNO, proving that the total neutrino flux interacting in this way corresponded exactly to the missing ν_e flux. A confirmation came from the KamLAND experiment in

▼ **FIG. 2: A. Bettini (left) and L. Maiani (right), together with a representative of local Swiss authorities celebrating at the "ground breaking" event for the CNGS project on 12/10/2000. Photo CERN**

Japan that observed the oscillation in anti-electron neutrinos from nuclear power plants.

By 1998 the Super-KAMIOKANDE [9] experiment had measured, with high statistics and high accuracy, the dependence of the atmospheric ν_μ flux on the flight-length and on energy. The shape of this function proved the oscillation phenomenon and made it possible to determine the corresponding oscillation parameters. Also in this case, confirmation of the oscillation interpretation came from disappearance experiments with artificial neutrinos, ν_μ produced at the KEK accelerators in Japan (K2K experiment) and later at the Fermilab in the USA (MINOS experiment).

From the third family to CNGS

As mentioned above, ν_τ and its charged partner τ are part of the third "family". As a matter of fact, the existence of the third family, and the concept of family itself, was experimentally established in the lepton sector much earlier than in the quark sector. We briefly recall that the neutrino was introduced as a "desperate hypothesis" by Pauli in 1930, when only the electron was known, to explain the apparent non-conservation of energy in beta decay. It was discovered in 1956, when also the muon had been discovered, by F. Raines [10]. It was in 1962 that an experiment at Brookhaven [11] established that neutrinos were two, ν_e and ν_μ. Not much later, the idea of the possible existence of a third lepton family, called "heavy lepton" H_l and its neutrino ν_{Hl} was introduced by A. Zichichi. The idea was to search for lepton pairs, which, in the case of $e^-\mu^+$ would be a clear signature of the H_l. The search started at CERN in 1963, with the PAPLEP experiment, and continued at the e^+e^- collider ADONE [12] at Frascati in 1967. The H_l did indeed exist, but was found, and called τ, only in 1975 by M. Perl [13] and collaborators at the SPEAR collider, which, differently from ADONE, had enough energy to produce it.

Thirty years ago, A. Zichichi, then president of INFN (Istituto Nazionale di Fisica Nucleare), succeeded in having approved by the Italian Parliament the Gran Sasso project, to build a large, technologically advanced, laboratory under the Gran Sasso massive. The laboratory halls were oriented, in particular, toward CERN, in order to be able in a future to host experiments on a neutrino beam from CERN. The draft presented by Zichichi to the Parliament is shown in Fig. 1.

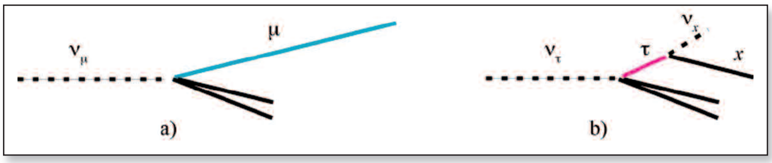
The vision started to become reality around 1997. Recalling that accelerators produce (almost pure) ν_μ beams, the alternative ν_μ disappearance vs. ν_τ appearance was open. Notice that they require different characteristics both for the beam and the experiments. Vivid discussions started in the community leading to proposals for both. In particular, the OPERA experiment was proposed in that year by A. Ereditato, K. Niwa and P. Strolin [14]. The study of the proposals led to a common decision by the CERN Director General, L. Maiani, the INFN President, E. Iarocci, and the LNGS Director, myself, for the more risky (but much more rewarding if successful) appearance experiments. The project was approved by the INFN and CERN Councils in 1999. It was funded with ad hoc contributions mainly from Italy and from several other countries.

Neutrinos do not behave as assumed in the **Standard Model** (SM): they do **change, "oscillate"**, between **one flavour** and **another**

The civil engineering works at CERN and the construction of the beam took place between Autumn 2000 (see Fig. 2) and Summer 2004. The subsequent delicate and complex phases of testing and commissioning were completed by the Spring 2006. In August of the same year the large detectors at LNGS, LVD, OPERA and BOREXINO detected the first events produced by the neutrino beam. In the same period the OPERA and ICARUS experiments were developed.

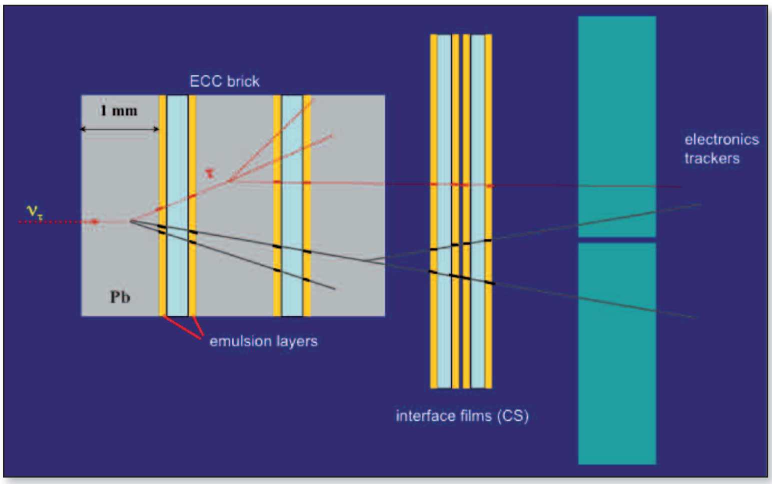
The first appearance

As mentioned, the beam produced at CERN is mainly composed of ν_μ with no ν_τ. Consequently, the observation of any ν_τ at LNGS must be due to the appearance in the oscillation phenomenon. Experimentally, the two types of neutrinos can be distinguished, when they produce a charged lepton: a ν_μ produces a μ and a ν_τ produces a τ. The principle is shown in Fig. 3.



▲ **FIG. 3:** Basic topologies of a) ν_μ interaction and, b) ν_τ interaction

▼ **FIG. 4:** The neutrino interaction detection principle of OPERA. Electronic trackers are used to identify the brick containing the interaction, which is then removed and processed.



In a tracking detector the μ appears as a long almost straight track, while the τ, which has a very short lifetime, picoseconds, decays already after few hundreds micrometres. Consequently, to observe the τ track a micrometre scale spatial resolution is necessary, something that only nuclear emulsions can provide.

However, there is a further problem. Indeed, even a distance of 730 km is small for the oscillation phenomenon, because the corresponding 2.5 ms flight time is only a small fraction of the oscillation period. Consequently, only a very small fraction of neutrinos, 1-2%, are expected to "oscillate". Considering in addition the very small neutrino cross section the conclusion is reached that the detector target mass needs to be considerably larger than 1000 tons.

This is why the "Emulsion Cloud Chamber" (ECC) technique, so called because it provides images similar to a cloud chamber, was chosen. It is based on sandwiches of thin (50 μm) emulsion sheets, providing the ~1 μm resolution tracking, interleaved with 1 mm thick Pb sheets, providing the mass.

ECC is a rather old technique, which was continually developed in Japan, with increasing levels of automation of the read-out, mainly at Nagoya. Historically, ECC detectors were successfully employed for the study of the high-energy cosmic-rays. Particularly important is the discovery by Kiyoshi Niu of a meson of a new flavour (in modern terms) in 1971 [15]. It was the charm, three years earlier than the discovery of hidden charm with the J/ψ particle by Burton Richter and collaborators and Samuel Ting and collaborators. The discovery of the ν_τ in 2000 by Kimio Niwa and collaborators [16] at Fermilab was obtained with an evolution of the same technique. OPERA is the latest and largest chapter of this evolution, composed, just to give a few numbers, of 150 000 sandwiches, called "bricks", including about 110 000 m^2 emulsion films and 105 000 m^2 lead plates, for a total of about 1250 tons.

ECC are, however, only a component of OPERA, which is a very complex structure: It includes different tracking elements and magnetic spectrometers, developed by the collaborators, both INFN groups and from other countries. The detection principle is shown in Fig. 4. Further fundamental elements are the automatic scanning and measuring microscope systems that are needed to extract the information from the emulsion. A big effort was invested in increasing by an order of magnitude the speed of these devices to cope with the above mentioned enormous emulsion area.

In 2008 – 2009 OPERA has collected about 1/5 of the total foreseen data; of these about 35% have been analysed and the first ν_τ candidate event has been already found[16]. It is shown in Fig. 5. The τ lepton is the short red track. It decays in a charged hadron, presumably a pion and a π°, which in turn decays into 2 gammas, which are detected. Even if the calculated probability for any background to simulate a τ is only 1.8%, it is too early to claim the discovery of the appearance phenomenon. But a few other similar events will hopefully lead to this long-awaited discovery in the next years. ■

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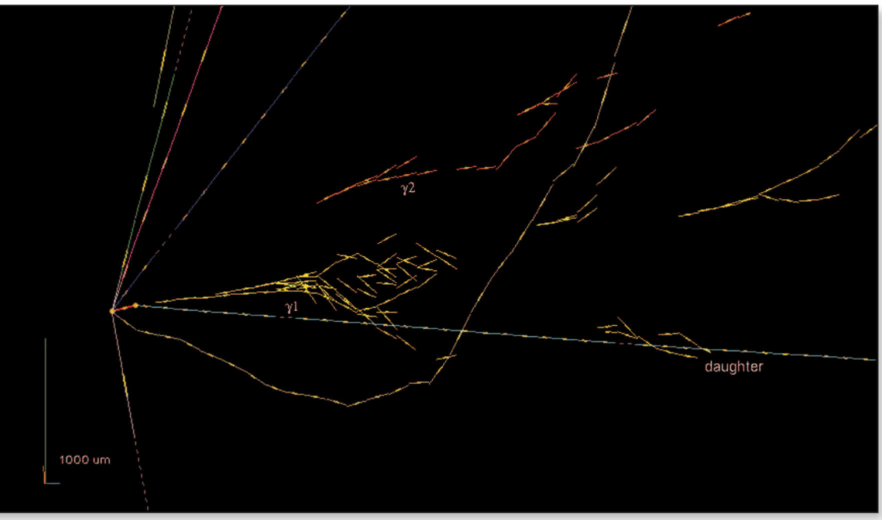
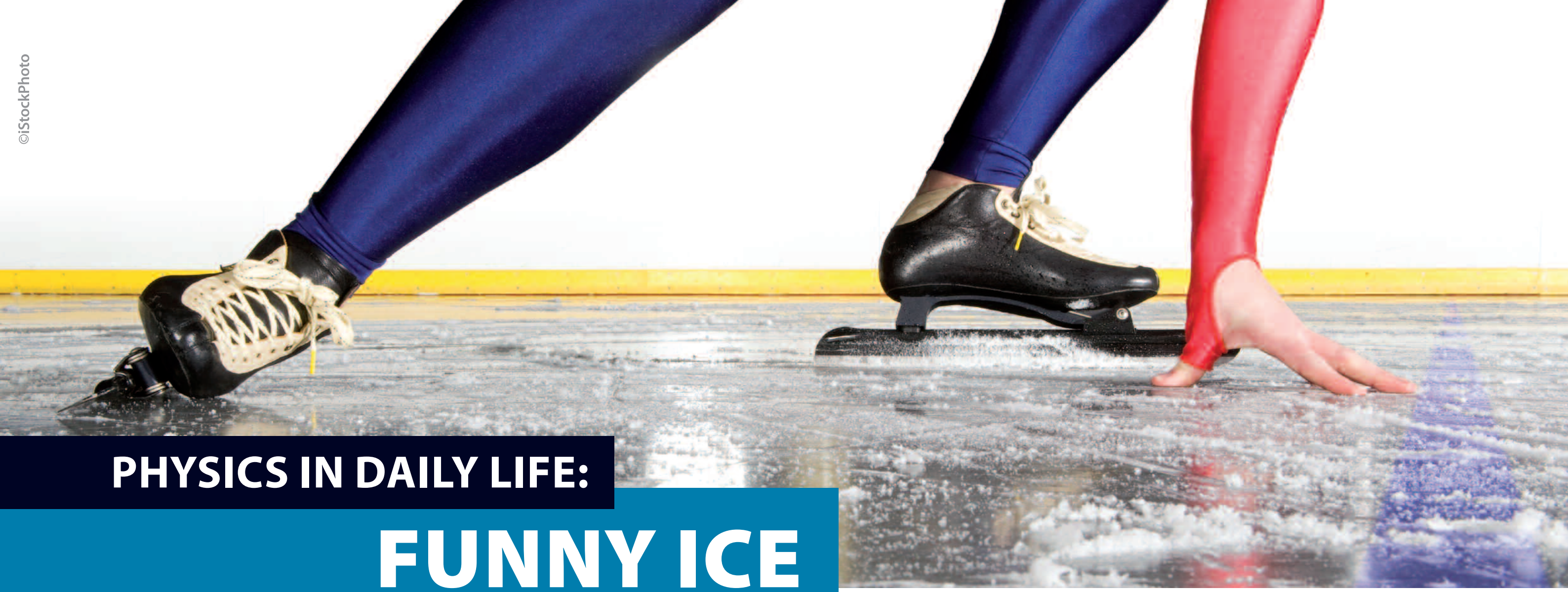


◄ **FIG. 5: The first ν_μ to ν_τ oscillation candidate. Notice the different scales on the two axes. Picture OPERA. You can watch an animation at http://dx.doi.org/10.1051/epn/2010604.s001**



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PHYSICS IN DAILY LIFE: FUNNY ICE

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Water is a great substance, especially when it freezes. It becomes slippery and is fun to skate on. But why is it that ice is so slippery? It is not because it's flat. Glass, for example, is flat but not slippery. What we need is a layer of water to turn a flat surface into a slippery one. And sure enough, if we skate on ice we skate on a thin layer of water.

So where does the water come from? Many people think it's because of the pressure that the skater puts on the ice. After all, pressure lowers the melting point, and a skater's weight on a tiny skate makes quite a lot of pressure. But if you do the calculation this turns out to change the melting temperature by a few tenths of a degree at most. So this explanation is wrong. Hardly surprising, when you consider that a hockey puck with its negligible weight slides so well across the ice. In fact, we don't need pressure at all. There is always a thin layer of liquid water on the ice, up to some 70 nanometres thick if the temperature is just below freezing point. Basically this is because the molecules in the uppermost layer miss neighbours at one side, so they are not as tightly bound as the molecules in the bulk. Therefore ice is wet, and that allows us to glide so beautifully almost without any resistance.

So much for the skating fun. What about the freezing process, if we consider still water that is not flowing? Of course, we need sub-zero air temperatures to do the trick. And as long as the water temperature is above 4 °C, natural convection mixes the water, since warmer layers near the bottom are lighter and rise. But once the water is at 4 °C, it has reached its highest density, so the coldest water near the surface is lightest and remains on top. Convection stops, and the freezing process can begin. This explains why shallow water freezes sooner than deep water.

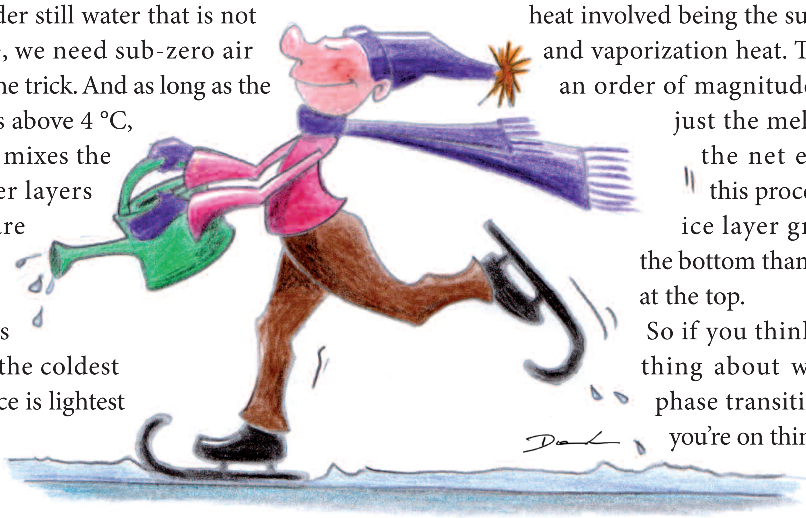
If the air temperature rises again, is there something special about melting of the ice layer? For reasons of symmetry we may expect that the melting process is just as fast as the freezing, if the temperature differences are supposed to be equal and opposite.

Wrong. During freezing in still cold air, the air layer just above the ice is warmer than the rest of the air. Natural convection now helps to cool the ice. By contrast, if the ice is melting due to rising air temperature, the ice is relatively cold, so the cold air next to it will have no tendency to rise. Convection will *not* set in to increase heat transport. We conclude that melting is slower than freezing.

Skaters hate to see the ice disappear. Fortunately, as long as the air temperature remains sub-zero and if we can ignore radiation, the thickness of the ice layer should remain unchanged. Or does it? We realize that, even below 0°C, there is a finite vapour pressure, so water molecules will go directly from the solid to the gaseous phase, by sublimation. Many skaters will conclude that this is bad news, since it will decrease the thickness of the ice layer.

Wrong again. Sublimation cools the ice surface, the heat involved being the sum of melting and vaporization heat. This is almost an order of magnitude larger than just the melting heat, so the net effect is that this process makes the ice layer grow faster at the bottom than it disappears at the top.

So if you think that everything about water and its phase transitions is trivial, you're on thin ice… ■



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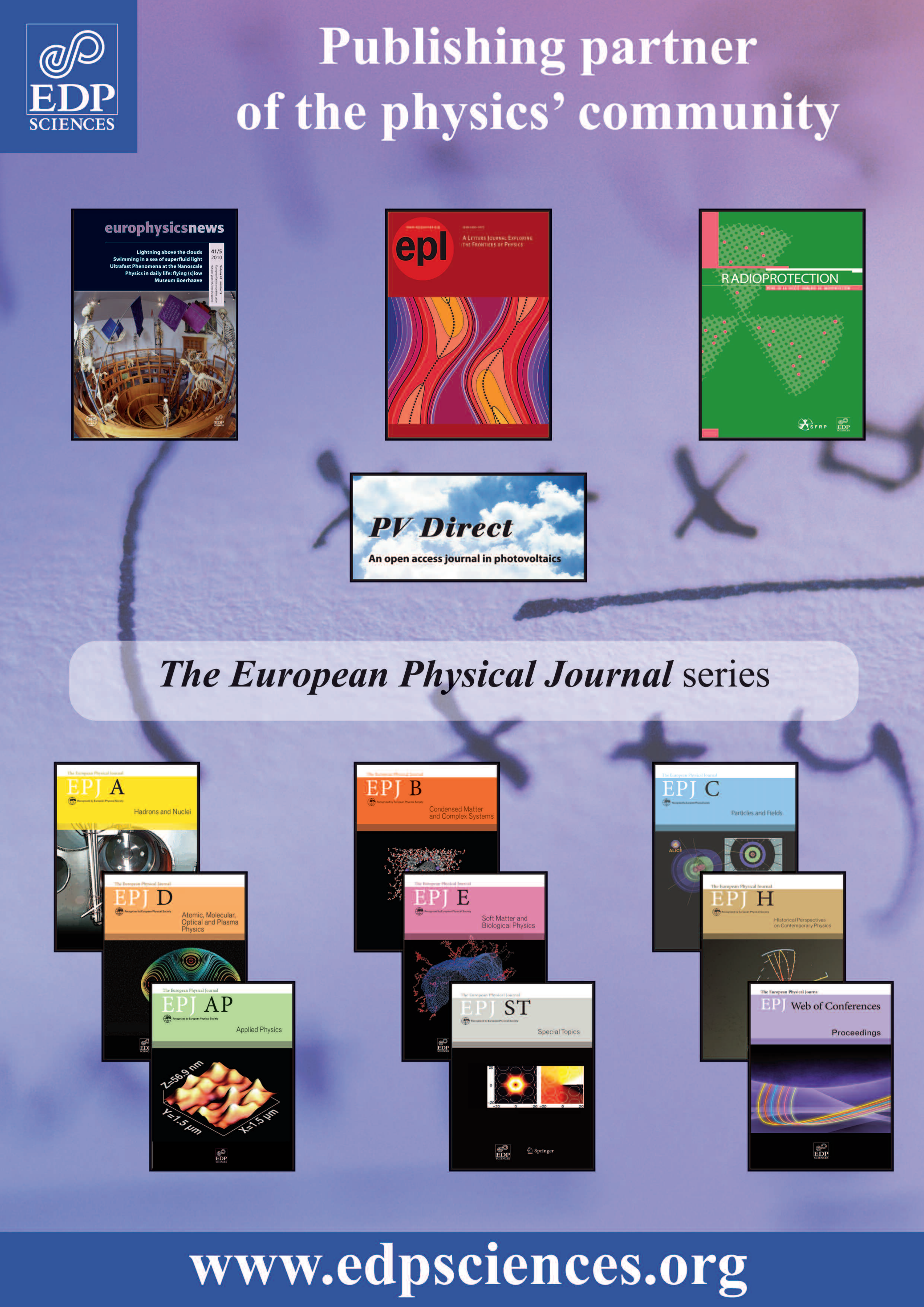
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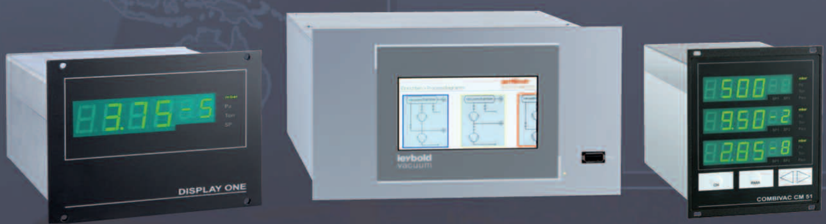

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