



Département
de Physique
—
École normale
supérieure

HIGHLIGHTS

DEPARTMENT OF PHYSICS
ÉCOLE NORMALE SUPÉRIEURE



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Editorial

The ENS Department of Physics, a historically leading research centre in France, has been rapidly evolving these past five years.

With the support of the State and the Ile-de-France region, the rue Lhomond building, where the department has been located since the Second World War, has been rehabilitated. It was a particularly challenging time as work was conducted in an occupied site, neither research teams nor administrative and technical services being relocated.

But thanks to the extraordinary involvement of the department's staff and the infallible support of the ENS and the CNRS, the quality of the building was greatly improved. Our working conditions have enormously benefited from this renovation, and we are now able to welcome students and visitors in pleasant surroundings that meet safety requirements.

It is remarkable that, despite the difficult context, our department has been able to remain active and produce research work of outstanding international importance. Many scientific world-leading results were produced, with one paper published each day in journals of high impact, and more than 40 doctoral dissertations defended each year. A lot of projects have been developed as evidenced by the 13 ERC grants that have been awarded to members of the department since 2012, the launch of several start-ups, and the creation of a Fablab to promote the creativity and innovation skills of students and researchers. Many new researchers have joined the department, our students have proved extremely successful in answering calls for proposals, our younger teaching staff have been deeply involved in national and international events aiming to promote physics, our technical and administrative services have shown the utmost ingenuity to help carry out all these projects and to meet the needs of our research teams...

With this brochure, we wish to illustrate the quality, wealth and diversity of the activities conducted at the Department of Physics. I hope it will contribute to make the department even more attractive and especially to incite young students to join us and share in our passion for scientific progress and education.

Our department will continue to evolve, the coming years being particularly significant. The renovation of our Grand Hall, which is to start in 2021, offers bright prospects in terms of space, better working conditions, improved organisation and greater opportunities to launch new projects. The planned merging of four of our laboratories is also expected to be an important source of renewal. I am convinced that our department's staff will know how to seize these opportunities collectively to increase its scientific reputation further.

Jean-Marc Berroir

Director of the Department of Physics at the ENS



140
permanent researchers and lecturers

90 administrative and technical staff

30 research teams

100 PhD students

100 post-docs

200 students

21 ERC

1 LabEx



Philippe Meyer Institute

Formation of topological defects in the merging of Bose-Einstein condensates

Sylvain Nascimbène, Jean Dalibard & Jérôme Beugnon

Bose-Einstein Condensates
Laboratoire Kastler Brossel (LKB)

How did the current structure of the universe emerge from the Big Bang? A partial answer to this question was put forward by T. W. B. Kibble in 1980: he suggested that connecting various parts of the universe with no previous causal contact should lead to the formation of so-called *topological defects* that eventually lead to the formation of galaxies.

The concept of topological defect was further transposed to various areas of physics, as shown by W. H. Zurek in the context of superfluid helium. A topological defect within a material is a certain type of defect that cannot be removed by smooth deformations of the material; it includes dislocations in crystals, stable waves denoted as solitons or vortices in quantum fluids. While topological defects at the cosmological scale have not been observed yet, they are ubiquitous in condensed matter physics.

The concept of topological defect plays a particularly important role in our current understanding of the dynamics of quantum systems crossing phase transitions, based on the so-called *Kibble-Zurek mechanism*. In this theory, the crossing of a phase transition comes together with the formation of topological defects, whose density increases with the speed at which the transition is crossed.

We investigated such a Kibble-Zurek mechanism using systems of ultracold atomic gases. Using laser cooling techniques and complex optical trapping landscapes, we can prepare a set of independent Bose-Einstein condensates, in a pattern shown below on the left image. Nine Bose-Einstein arranged along an annulus can then be made to merge together, leading to a uniform density profile after several milliseconds of relaxation.

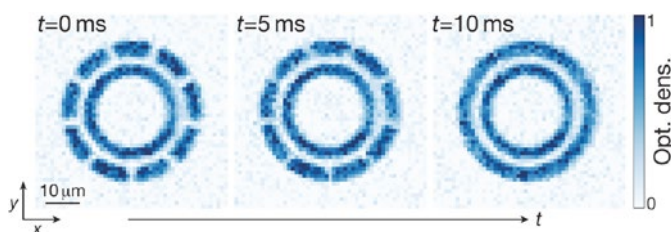


Fig. 1 In situ images of the ultracold gases before, during and after the merging of several Bose-Einstein condensates. The atom confinement is provided by light beams acting as repulsive barriers, the shape of which being tailored using a matrix of micro-mirrors. The barriers separating the Bose-Einstein condensates along the external annulus are removed at the time $t = 0$, leading to a merging of the condensates on a 10 ms timescale.

But this annular Bose-Einstein condensate is not necessarily at rest : it may flow along the annulus, and as a superfluid system, we expect its circulation to be quantized. We probe this circulation using matter-wave interference with the inner

annulus, which is initially prepared at rest. The circulation measurement proceeds as follows: by cutting the trapping potential, the two annula are made to overlap and interfere. The interference pattern is made either of concentric rings, or shows a spiral pattern that allows to infer the quantization of circulation, see figure below. This observation shows that topological defects – here supercurrents – can emerge stochastically from the merging of independent quantum systems.

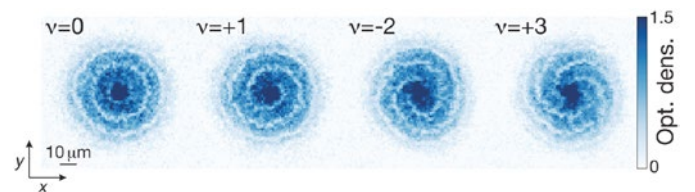


Fig. 2 Probing the phase winding of the macroscopic wavefunction. The two annular gases are released from the trap and made to overlap, leading to matter-wave interference. The observation of spiral patterns reveals a non-zero phase winding, corresponding to the flow of a super-current.

We investigated the mechanism behind this behavior, and showed that the statistics of supercurrent formation is determined by the geodesic rule, following a simple geometry argument. We also explored the underlying mechanism occurring when merging two condensates. Our observations suggest the formation of soliton-like phase defects whose dynamics eventually relax towards the formation of stable supercurrents.

Future experiments could investigate more precisely the relaxation mechanism, by imprinting a given phase difference between neighboring condensates. This should allow us to observe the appearance, motion and decay of soliton defects. More generally, this kind of study can be generalized to other cold atom settings, allowing to investigate non-equilibrium physics in various types of quantum phases of matter.

FURTHER ON

Aidelsurger et al., *Phys. Rev. Lett.* 119, 190403 (2017)

INTERVIEW

Nabil Garroum, research engineer in charge of the FabLab

Fablabs have been rapidly developing these past years. Can you tell us what they are?

A Fablab may be seen as a bridge between research and training, a place of scientific and technical collaborations between engineers, researchers, and students. Very concretely, today it fills a room and includes measurement equipment (oscilloscopes, signal generators), but also 3D printers and microcontrollers (Arduino). Students are free to use the Fablab to make their own experiments. It is designed for all sorts of projects, be they scientific, technical, or even creative.

What makes the Physics Department's Fablab unique?

While Fablabs are usually embedded in discussions about matter of concerns for the general public, the ENS Fablab is more focused on experimental physics. But of course, this does not exclude interactions with other disciplines. Because of the limited number of students at the ENS, our Fablab remains reasonable in size, which facilitates and stimulates collaborations with academics. Students can therefore address the concepts of experimental physics very practically.

What are the Fablab's objectives?

It focuses on digital fabrication, including additive fabrication and the programming of electronic microcontrollers. It aims at enabling students to experience the concrete process of doing things by themselves and reflecting about it. They thus become aware of some fundamental aspects of research work and scientific instrumentation. The Fablab will soon be open to PhD candidates who need it to carry out their projects.

The Fablab has been used by students during the French Physicists' Tournament, in which student teams compete to solve physics problems.

It is also open to students with their own personal projects, such as building a telescope, an anemometer, a robot, a drone, a 3D printing head, optical lenses, Thorlabs optical mounts. Students are encouraged to do things themselves on the principle of DIY (Do-It-Yourself) and RepRap (Replication Rapid prototyper). While we have known how to build telescopes for a long time, the Fablab makes it possible to experiment with mirrors of different shapes and sizes in a matter of hours and for a far lower cost than usual production methods would require.

The Fablab is also used to make gifts, such as the 3D pictures that are prepared by the department's staff at Christmas, or designer objects, some of which can only be made using 3D printing (cf. the fractal pyramid on the picture!). Finally, the FabLab tackles social issues: a discussion is initiated with Ecocampus (association which is in charge of implementing actions related to sustainable development) in order to carry out green projects with an environmental dimension.

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Short terahertz pulse generation from a semiconductor laser

Sarah Houver & Sukhdeep Dhillon
Ultrafast THz Spectroscopy
Laboratoire Pierre Aigrain (LPA)

In the terahertz (THz) frequency range, i.e. at the interface of electronic and optical domains, a semiconductor-based technology platform for ultra-short pulse generation has yet to be realized, despite potential applications in spectroscopy and communications. Here, the authors use quantum cascade lasers (QCLs) combined with a novel dispersion compensation scheme, based on a Gires-Tournois Interferometer. This allow to generate ultrashort THz pulses with a duration of a few optical cycles, opening up new applications in metrology and ultrafast detection.

Modelocked semiconductor lasers are an underpinning technology throughout the optical and near-infrared regions. This has permitted the generation of ultrafast, intense and stable light pulses that can be applied to a plethora of applications across the physical, chemical and biological sciences, from nonlinear optics to corneal surgery. However, in the terahertz (THz) frequency range with potential applications from imaging to non-destructive testing, a modelocked semiconductor technology platform for ultra-short pulse generation has yet to be realised. Although THz quantum cascade lasers (QCLs) are semiconductor-based, where intersubband transitions can be engineered to emit over the ~1 – 5 THz spectral range, pulse generation has been expected to be difficult. This is a result of the ultrafast gain recovery time inherent to QCLs that is considerably shorter than the photon round-trip cavity time. This is in contrast to the dynamics of other laser diodes and prevents the generation of few-cycle pulses in the THz range. Here we show that this is in fact not a limiting factor, and it is fact the index dispersion that is the limiting factor.

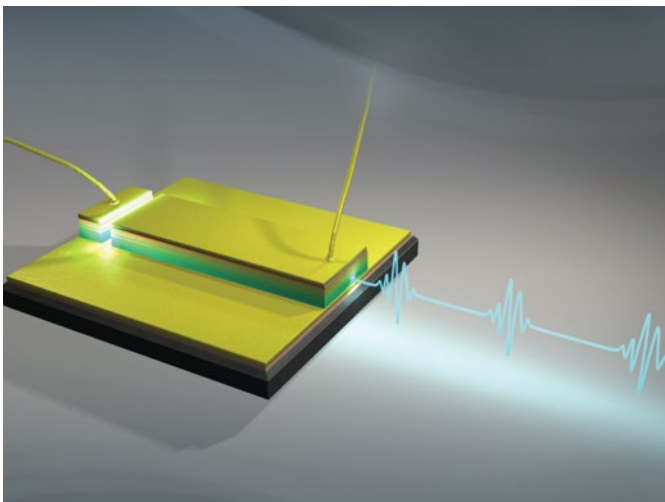


Fig. 1 Schematic of QCL with integrated GTI to prevent THz pulse stretching via dispersion.

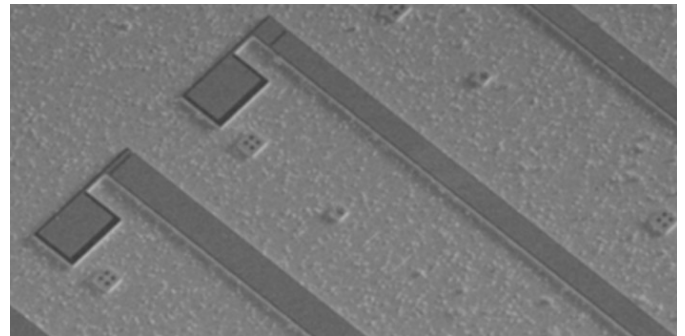


Fig. 2 Processed sample showing coupled cavity scheme for the realisation of a monolithic GTI where the long section is the QCL cavity and the short section is the GTI.

To generate ultrashort pulses from a laser, the following components are required i) a gain within a laser cavity; ii) a modelocking mechanism such as the fast modulation of the losses or gain at the cavity round-trip and iii) dispersion compensation. The first two points have been widely investigated. Regarding the third point, dispersion indicates that the refractive index varies with frequency and this dispersion is undesirable for short pulse generation. It is often characterized by the group delay dispersion (GDD). This parameter is critical in ultrafast lasers and indicates how a pulse broadens as it propagates within a material with an uncompensated dispersion (a non-zero GDD), and GDD becomes increasingly important for shorter pulses (corresponding to a large spectral bandwidth). In the case of the optical and NIR spectral regions, dispersion compensation in femtosecond lasers is readily accomplished with internal or external elements such as prisms, grating or chirped mirrors that introduce a GDD that is opposite to that of the laser medium. This brings the overall GDD down to zero and limits the broadening of ultrashort pulses. However these concepts are difficult to export to the THz range owing to the large wavelengths of the generated photons.

In this paper, we resolve the THz QCL short pulse bottleneck through a novel on-chip geometry that permits the GDD of the QCL to be compensated, leading to considerably shorter

pulses when the QCL is active mode locked. This is realized through the monolithic integration of a small resonator at one end of a 2.5 THz QCL cavity (schematically shown in the below figure), based around a Gires-Tournois Interferometer (GTI) approach that adds an opposite dispersion to that of the material. By judiciously designing the length of the integrated GTI, applying the GTI between the Fabry-Perot resonance of its cavity ('off-resonance'), and exploiting the QCL waveguide, significant compensation of the QCL's inherent GDD can be achieved. This directly results in pulse durations as short as 4 ps, considerably shorter than the state-of-the-art, with a continuous Gaussian spectral range extending from 2.3 to 2.9 THz. The dispersive effect of the GTI mirror is clearly demonstrated by characterizing a GTI of a length that results in zero dispersion compared with one that introduces too much dispersion. The former shows a stable ultra-short pulse train while the latter destroys the pulse formation. This is further confirmed by characterizing the free running electrical beat note that show a very narrow linewidth for correctly dispersion compensated QCL. As the GTI is applied 'off-resonance' and not in the typical 'on-resonance' case, this relatively simple approach can be easily scaled to compensate for even greater spectral bandwidths and potentially attain sub-picosecond pulse widths. This would rival pulse generation from large and complex femtosecond excited THz sources.

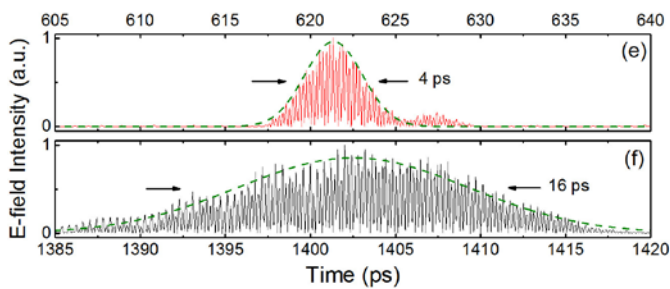


Fig. 3 Short pulse generation for QCL with GTI (red curve) showing 4 ps pulse generation compared to standard QCL (black curve)

This work solves a longstanding problem on ultrashort pulse generation from QCLs and will stimulate new concepts to generate shorter and more intense pulses in the THz range using a semiconductor source. This work is a pan-European collaboration between groups in France, UK and Germany, and performed in the context of a FET-OPEN project ('ULTRAQCL' grant number 665158) for the realisation and application of short THz pulse devices to subjects as varied as spectroscopy to quantum optics. It is an active field with a range of international groups working on the subject. Further the perspectives of this work will impact other research areas such as dual frequency comb spectroscopy that can be manipulated by microwave generators.

FURTHER ON

Feihu Wang et al, *Laser and Photonics Review*, 11 1700013 (2017)



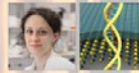
Département de physique
Ecole normale supérieure

Colloquium 2017-2018

3e trimestre



03/04 : SABRINA MANISCALCO (UNIVERSITY OF TURKU)
Saving the Quantum:
how to make friends with the environment
Salle Jean Jaurès - 17:15



15/05 : ALEKSANDRA RADENOVIC (EPFL)
Nanopores in 2D materials
Salle Jean Jaurès - 17:15



29/05 : WILLIAM BIALEK (PRINCETON UNIVERSITY)
Towards a renormalization group for networks of neurons
Salle Jean Jaurès - 17:15



12/06 : AMITAVA BHATTACHARJEE (PRINCETON UNIVERSITY)
Fast magnetic reconnection
in space and astrophysical plasmas
Salle Jean Jaurès - 17:15



26/06 : WILLIAM YOUNG (University of California, San Diego)
Long-range propagation of ocean swell
Salle Jean Jaurès - 17:15

COLLOQUIUM

How to stay in touch with the latest significant developments in all areas of physics? The Colloquium is intended for all members of our department, and beyond, to gather on a regular basis, to have a casual chat over a cup of coffee and some biscuits, and to stay abreast with the major progresses of our discipline.

Colloquia are given by world-renowned experts and talented speakers. Their mission is to give a pedagogical overview of their research field, and share with us their latest remarkable results. Everyone in the department is pressed to participate, from student to professor: it's a healthy practice of science!

The list of speakers for the year 2017-2018 included Profs. J.-P. Sauvage (chemistry, Strasbourg), M. Kasevich (atomic physics, Stanford), J. Bloch (nanoscience, Paris-Saclay), B. Allen (gravitational physics, Max Planck), G. Kotliar (condensed matter, Rutgers), S. Maniscalco (quantum optics, Turku), W. Bialek (biophysics, Princeton), A. Bhattacharjee (astrophysics, Princeton), W. Young (oceanography, UCSD), etc.

The detailed program is available on the SEMPARI server or the department's Google calendar. The colloquia are recorded and the videos are also available on our Youtube channel as soon as ten days after.

- > [Department Outreach](#)
- > [Youtube channel](#)

Mechanical DNA sequencing: from research to an innovative start'up

Jean-François Allemand
ABCD Lab
Laboratoire de Physique Statistique (LPS)

A common unpleasant experience in winter is to have a jacket zipper blocked by a scarf. At the molecular level a similar behavior can be observed by replacing the zipper by a double strand DNA and the scarf by a synthetic oligonucleotide complementary to one part of the DNA.

The closing or opening of a hairpin structure (see Fig. 1) can be performed by using a magnetic bead attached to a probed DNA on one end while the other end is attached to a glass surface. Magnets placed above the sample can be used to exert a small or a large force on the molecule to stretch it. The closer the magnet to the bead the stronger the force. Above a critical force threshold, the famous DNA double helix cannot sustain the tension and the bonds between the bases on each side of the helix break. As a result, the molecule's extension increases and the bead's position changes. The change in extension at ~ 20 pN is about 1nm/base. But when the force is reduced, due to molecular recognition between complementary bases the double helix refolds spontaneously and very quickly. When a small segment of DNA (an oligonucleotide) in solution has a sequence complementary to an exposed part of the probed DNA, as is the case at high force, it will bind to the opened molecule for the same reasons that explain the refolding of the double helix. As a consequence, DNA refolding at low force is transiently blocked by that small oligonucleotide. Since, in principle, one knows the oligonucleotide sequence the presence of a blockage is a signature that the complementary sequence is present on the probed molecule and its extension at the blockage gives the position of the sequence on the DNA. Measuring the position with a single base resolution allows DNA sequencing, if one probes blockages with a library of nucleotides. DNA chemical modifications, known as epigenetic modifications, can be detected similarly using molecules (proteins) that recognize and bind to these modifications.

The expected low error rate of the sequencing and more crucially the ability to probe without any amplification DNA sequence and epigenetic modifications provides a unique approach to the growing field of epigenetics. After being discovered in the ABCD lab this approach was patented and is developed by Depixus (www.depixus.com), a start-up co-founded by the inventors. It has been selected as one of 58 small companies to receive a start-up phase grant in the Concours Mondial d'Innovation (Worldwide Innovation Challenge).

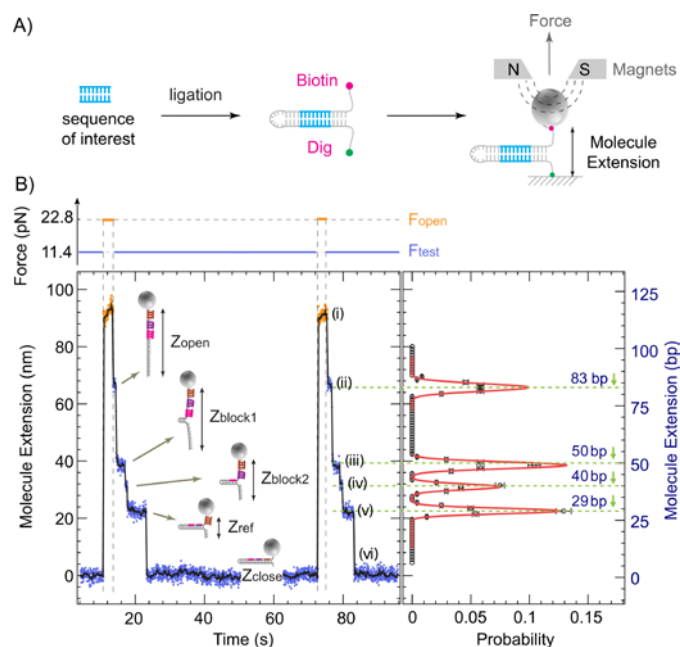


Fig. 1

FURTHER ON

Ding F. et al., Nature Methods, published online: 11 March 2012

Carbon nanotubes tune single photons

Adrien Jeantet, Yannick Chassagneux & Christophe Voisin
Nanooptics
Laboratoire Pierre Aigrain (LPA)

Carbon nanotubes are long known as one-dimensional semi-conducting nano-emitters of light. The diversity of their structures offers an original handle to choose their working wavelength on a wide range covering the technologically relevant telecommunication bands in the near infra-red (1.3-1.55 μm). In addition, it was demonstrated a few years ago that their emission at low temperature consists of single photons. This means that they emit one photon at most per excitation light-pulse.

These individualized photons are an essential building block for future quantum secured telecommunications. However, the low luminescence quantum yield of nanotubes and their extreme sensitivity to local environment fluctuations have long hampered technological developments in opto-electronics. Recent breakthroughs in supramolecular chemistry and integration in photonic structures, such as micro-cavities, have put them back on track as alternative sources of single-photons. Presently, carbon nanotubes make up the only known solid-state source of single-photons capable of being operated at room temperature and in the telecom wavelength bands.

In this context, the Optics group at Laboratoire Pierre Aigrain, in collaboration with the Atom chip group at Laboratoire Kastler Brossel, has developed a versatile method to couple a single nanotube to a micro-cavity. This required to tackle two challenges : a spatial matching of the cavity to the nanotube, with a submicrometric accuracy and a spectral matching with a subnanometric accuracy. These matching issues are critical due to the large variability of the nanotubes properties and to the random location of nanotubes in regular sample preparation processes, which jeopardizes standard integrated photonic approaches. To this end, we developed a reconfigurable fibered cavity associated to a home-made confocal microscope (see Fig. 1). The latter is used to localize and fully characterize a single nanotube. The cavity parameters are then adjusted accordingly to provide the best coupling parameters to the particular nanotube.

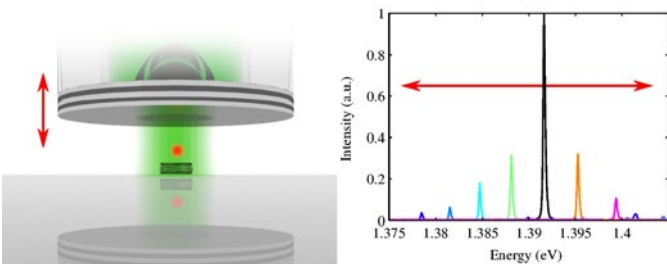


Fig. 1 (left) Principle of the versatile fibered micro-cavity engineered at the apex of an optical fiber. The red bullet symbolizes the single photon emission, while the green shaded area represents the cavity mode. The red arrow shows how to tune the cavity resonance through a mechanical displacement of the fiber.

Fig 2 (right) The single-photon source can be tuned on a wide range exploiting the cavity feeding effect on acoustic phonon side-bands of the exciton. The red arrow shows the achievable tuning range, in echo to the fiber displacement on the left panel.

Using this technique, we achieved a strong brightening of nanotubes (the so-called *Purcell effect*) with a 20-fold increase of the effective luminescence quantum yield. Meanwhile, it remains a high-quality single-photon source (98 % antibunching, meaning that the probability to get more than one photon per cycle is below 2 %) with a polarization purity better than 90 %. With an almost perfect extraction efficiency, this system provides a near-infrared single-photon source with a brightness up to 0.35, in line with the best single-photon sources available to date.

Nevertheless, the main originality of our system resides in its strong one-dimensional character, in particular as regards the coupling of electrons to acoustic phonons. Combined with the strong Purcell effect achieved with our cavities, this phonon coupling turns out to be an invaluable resource to explore the so-called cavity feeding effect, a typical quantum optical effect. This effect describes the possibility to drive the emission wavelength of an emitter through that of a photonic resonator -even for a large detuning between their respective resonances- while keeping a strong emission efficiency. This allowed us to dramatically increase the tuning range of the single-photon source, a property barely achievable with alternative systems. By exploiting the flexibility of our cavity design we were able to operate our source over a wavelength range covering several hundreds of the cavity natural width while maintaining a brightness much above that of the bare emitter (see Fig. 2).

In the future, this system will be used to explore advanced photonic effect such as few-photon nonlinearities that are supposedly strong in 1D systems due to the reduced screening of Coulomb interactions. Such a device could make up a building brick for all optical information processing in future telecommunication schemes.

FURTHER ON

A. Jeantet et al., *Phys. Rev. Lett.* **116**, 247402 (2016)

A. Jeantet et al., *Nano Letters* **17**, 4184 (2017)

Experimental demonstration of an invariance property of waves in complex media

Sylvain Gigan & Romolo Savo
Optical Imaging in Complex and Biological Media
Laboratoire Kastler Brossel (LKB)

The understanding of light propagation in complex media is both a fundamental problem, tackling several major issues in mesoscopic physics such as Anderson Localization, highly relevant for the design of novel photonic structures, and the key to unravel imaging techniques able to penetrate deep into biological tissues, which are opaque to light due to their highly heterogeneous nature at the microscale. In a recent work, we demonstrated a very general property of light scattering in complex media, namely that the average path length for light in a structure only depends on its geometrical properties, but not at all on its microstructure.

We know that light, and a wave in general, propagates in straight lines in homogeneous transparent media. If the medium is perturbed, however, the light is deviated. For instance, clouds, made of small droplets of water in suspension, appear milky, since every droplet can deviate or scatter light. At low concentration, one can see through it, but at strong concentration the cloud becomes dense and opaque. Similarly, an ice cube is transparent, but snow, also made of water, is opaque because made of many small crystals. This very strong relationship between the structure of a material and its optical behavior is at the root of a wealth of optical devices and phenomena, from heat transfer in the atmosphere, iridescent colors of butterflies, information storage in a DVD, telecommunication in fibers, and even many sensors. In the context of a collaboration between the team of the LKB (Sylvain Gigan, Romolo Savo, Ulysse Najar) of the Langevin institute (Rémi Carminati and Romain Pierrat) and TU Wien in Austria (Stefan Rotter), we have experimentally demonstrated a new property of light, namely that there exists a quantity independent of the microstructure: the average path length in a given volume, defined as the total length traversed by the light between entering and exiting the sample, for all possible incident position and angle.

As predicted in 2014 in a theoretical article from the same collaboration, the mean path length indeed is predicted not to depend on the microstructure, but only on the geometrical properties of the medium under investigation, such as its volume or its external area. More precisely, the average path length is expected to be :

$$\langle s \rangle = 4 \frac{V}{\Sigma}$$

where $\langle s \rangle$ is the average path length, V the volume and Σ the outer surface of the medium.

Experimentally, the demonstration was performed by measuring the path length distribution for light in a glass cell containing a solution of water to which small particles were added. Measuring directly the time-of-flight distribution of light is very challenging, since it spans over several orders of magnitude in time and intensity. We therefore chose another approach, which is to determine the mean path length indirectly by shining a continuous laser on the medium, and inferring the distribution from how fast the speckle (the interference pattern generated by the scattering process) changes over time due to the Brownian motion of the scatterers. By varying the concentration of the particles of nearly two orders of magnitude, the medium spans from nearly transparent like water to very opaque, like milk, and the distribution of the path changes tremendously. However, the mean value of the path length was observed to be constant, thus confirming the theoretical prediction. This property, verified here for a totally disordered material, should in principle be valid whatever the heterogeneity of the medium, strong or weak, ordered or disordered, at short or large scale.

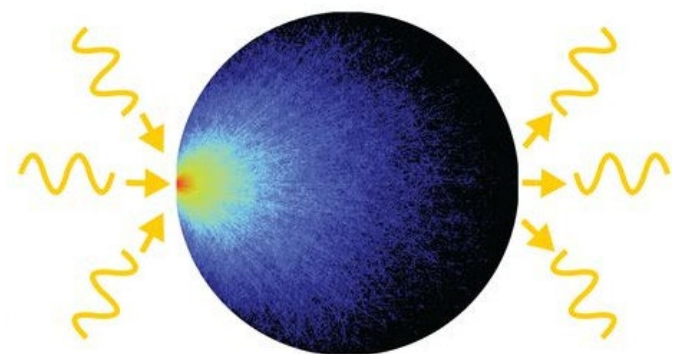


Fig. 1 Simulation for the trajectories of light in media ranging from quasi-transparent (where light is nearly ballistic – straight lines) to very scattering (where light follows trajectories similar to random walks). The result demonstrated here experimentally is that the average path length if the same in all these media.

Beyond its fundamental interest (an invariant quantity in physics being generally the manifestation of a very fundamental principle), this result, thanks to its generality, could impact many domains in optics, and in physics in general. Indeed, the invariance demonstrated here for light is valid for any type of waves, and also applies to other transport phenomena (heat of particle). It is also relevant for the understanding of other complex phenomena that are described by physical models, such as bacteria movements or financial markets.



Fig. 2 Liquid samples with various concentration of microbeads, ranging from nearly transparent to very opaque, used in the experimental demonstration. All samples, despite their very different optical properties, share the same average path length.

THE TEAM

The team «optical imaging in biological and complex media» of Laboratoire Kastler-Brossel deals with light propagation in complex media, mainly disordered photonic systems where light is scattered in a very complex way, such as paint layers, paper, or biological tissues. Multiple scattering of coherent light generates extremely complex interference patterns, called speckle. But despite the enormous complexity of the scattering process, we can exploit and control light propagation, in particular thanks to spatial light modulators. Our approach is particularly interesting for imaging, light-matter interactions, signal processing, but also as windows to understand subtle mesoscopic physics effects.

FURTHER ON

R. Savo et al., *Science*, 358(6364), 765-768 (2017)



FRENCH PHYSICISTS' TOURNAMENT

For four years now, some of our students have been taking part in the French Physicists' Tournament (FPT), an initiative launched by a group of PhD candidates and hosted by the French Physics Society (Société Française de Physique). The tournament involves an experimental training to research combined with a national event gathering students from a dozen universities and grandes écoles who share the same ideal: to discuss, exchange and debate physics.

Each year, in early September, organisers publish 11 open physics problems. Students have five months to try and provide an answer as precise as possible. Here are some examples: *Why does a balloon rubbed against human hair stick to a ceiling? What is the maximum temperature in a greenhouse? Build the most efficient magnetic cannon, and study its parameters.*

Open problems offer an opportunity to become familiarized with research work, and this is what particularly attracted us, since they resonate perfectly with the training spirit at the ENS. Preparing for the tournament is now credited with ECTS points, like any experimental project, and students are supervised by some of the department's researchers who provide support during the key steps of this research training: finding bibliographic references, establishing an experimental protocol, organising a rigorous measurement campaign, and so on. We work in close collaboration with the Fablab, which provides a suitable playground for experiments, as well as with an experimental platform, located in Montrouge.

The tournament is in itself a wonderful opportunity for students to speak at a scientific event: during discussions in English, they must present and explain their results by synthesising several months of research, and highlighting orders of magnitude and the relevant physical processes accounting for various phenomena. They must also provide a critical analysis of the work of the other teams and try to find a collective solution to the problem.

By giving students an early taste of research through this intensive training, we hope that they develop an appetite for it!

Arnaud Raoux

Professeur agrégé at the Department of Physics and organiser of the French Physicists' Tournament

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Flows at the nanoscales, from exotic transport to application for blue energy

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Nanofluidics is the frontier where the continuum picture of fluid mechanics confronts the atomic nature of matter. Recent experiments reported exceptional transport properties of water when confined in carbon nanopores. This has stimulated interest in carbon-based membranes for desalination, nano-filtration, and energy harvesting. But these works raised fundamental questions on the specificity of the water-carbon interface, its structure, reactivity and dynamics. The Micromégas team of the Laboratoire de Physique Statistique could measure for the first time the flow of water through an individual nanotube. This required to invent new instrumental approaches reaching unprecedented sensitivity to measure minute flows and ionic currents. These measurements demonstrate that water flows nearly frictionlessly in carbon nanotubes, in strong contrast to their boron-nitride counterpart. This points to an unexpected link between hydrodynamics and the electronic properties of the confining matter. Beyond, such exotic transport phenomena at nanoscales point to new solutions to harvest the energy generated by salinity gradients, the so-called blue energy.

It is an exciting period for nanofluidics, the field which explores the transport of fluids at the nanoscales. After a decade of developments, routes are now opened to fabricate individual channels with nanometric and even sub-nanometric dimensions. New instruments and tools have also been invented in order to reach the proper sensitivity to measure and characterize the fluid and ionic transport across these ultimate channels. Fluid transport at the smallest scale is a *terra incognita*, a virgin territory which remains to be explored. And indeed, a number of quite exotic properties have emerged since, many of them still remaining to be understood.

One such counterintuitive result was first reported ten years ago, showing super-fast water transport across membranes made of carbon nanotubes a few nanometers in diameter. The permeability of the nanotubes, which quantifies the fluid velocity under an imposed pressure drop, was measured to be up to four orders of magnitude larger than guessed from simple hydrodynamic estimates. The underlying dynamics and mechanisms of water transport inside nanotubes remains mysterious. The nearly friction-less flows of water inside nanotubes defies the theoretical understanding and the conflicting results between the few available measurements across nanotube membranes led to a strong controversy. There is therefore a concerning lack of experimental output, mostly because investigations in this domain are extremely challenging. Accordingly, advancing our fundamental understanding of fluid transport on the smallest scales requires flow and ion dynamics to be ultimately characterized across an individual channel to avoid averaging over many pores. A major challenge for nanofluidics thus lies in building distinct and well-controlled nanochannels, amenable to the systematic exploration of their properties.

To address this challenge, the Micromégas team has developed a number of tools which allow to fabricate nanofluidic devices involving a single nanotube amenable to fluidic measurements. An extensive nanomanipulation toolbox allows to displace, assemble, glue, cut, mill, etc. nanotubes and 2D materials like graphene, with these operations being performed *live* under the beam of an electronic microscope (SEM). With these tools, it was possible for example to fabricate a hierarchical nanofluidic device made of a single (carbon or boron-nitride) nanotube that pierces an ultrathin membrane connecting two fluid reservoirs. This device allowed to fully characterize the ionic transport across individual carbon and boron-nitride nanotubes under a wealth of driving forces characteristic to fluid motion: electric fields, pressure drop, but also osmotic drivings.

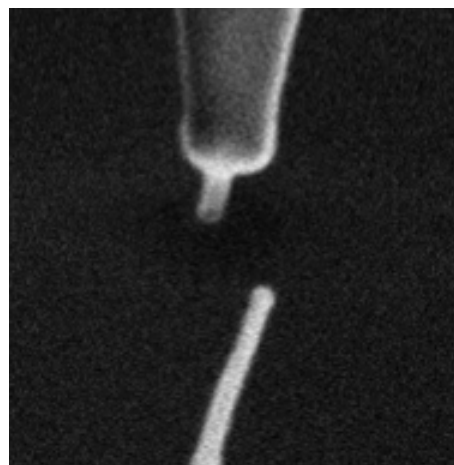


Fig. 1 Insertion of a nanotube at the tip of a nanopipette thanks to nanomanipulation under a SEM.

With the nanomanipulation strategy, it is also possible to develop alternative assemblies, such as a nanotube sealed to a nanopipette, akin to a nano-pen (see Fig. 1). This latter geometry was a key to characterize the permeability through single nanotubes. Indeed, as compared to the state of the art methodologies for flux measurements, quantifying the water flow through a single nanotube required to boost the sensitivity of instruments by at least three to five orders of magnitudes, a performance which is still beyond reach. The nano-pen assembly then suggests an alternative route for flux measurements, which consists in studying the *jet-flow* created through a nanotube into a reservoir, once a pressure drop is applied. The physical properties of the jet-flow created by a nozzle geometry were first predicted by Landau and Squire more than fifty years ago, but largely overlooked and unexploited. Interestingly it has some peculiar physical characteristics because a minute flow emerging from the nozzle tip is able to move *massive* amounts of water in the reservoir, akin to a flow amplifier. This is exemplified in the figure below, which shows the flow streamlines in the reservoir induced by a jet flow emerging from a 33nm in size nanotube: in spite of the nanoscale of the nozzle, a considerable flow is generated in the reservoir, which extends over tens of microns. A detailed analysis of this Landau-Squire jetflow pattern then allows to retrieve the transport properties across the nanotube, hereby providing its permeability, the quantity at stake.

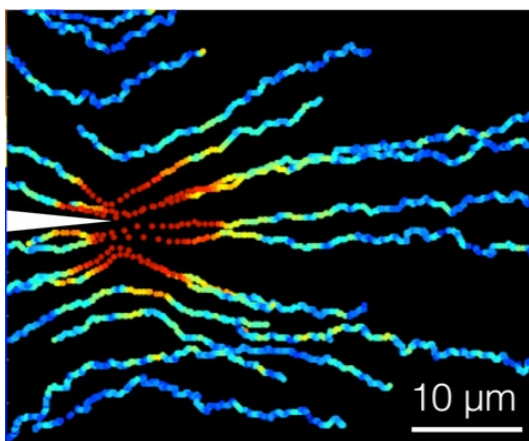


Fig. 2 Flow streamlines in a water reservoir measured by the motion of tracers, and highlighting the Landau-Squire jet flow generated across a nanotube 33nm in size.

The results, as shown in Fig 3, highlights a giant permeability of the carbon nanotube, which is much larger than the standard hydrodynamic (Poiseuille) prediction and furthermore increases when the tube radius decreases. In contrast, the boron-nitride nanotube - the crystallographic cousin of the carbon nanotube - fully agrees with the Poiseuille reference. That these two materials which have the same structure but different electronic properties - boron-nitride being strongly insulating in contrast to semi-metallic carbon - exhibit such different flow behavior points to a hitherto not appreciated link between hydrodynamics and the electric structure of the confining materials. These behaviors remains to be understood. Such results open an exciting bridge between hydrodynamics and condensed matter, as a playground where *classical meets quantum*.

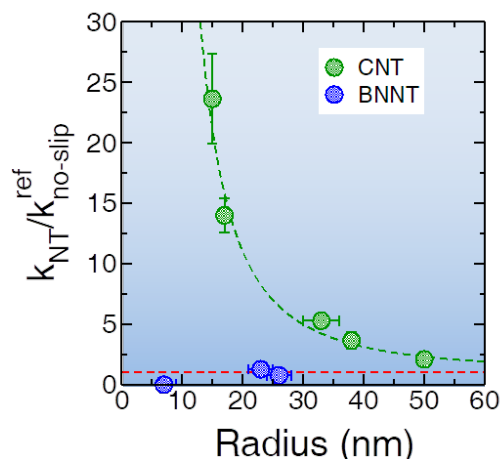


Fig. 3 Permeability of individual nanotubes as a function of the tube radius, for carbon (green) and boron-nitride (blue) nanotubes. The permeability is compared to its classical Poiseuille reference (assuming no-slip).

Carbon is accordingly very special from the fluidic perspective. But actually boron-nitride material also brings its share of surprises. For example the study of ionic transport across boron-nitride nanotubes has demonstrated the generation of huge electric currents under salinity gradients. This discovery has unexpected consequences in the so-called blue energy domain, which aims at developing a new form of energy conversion based on the salinity difference between, say, sea water and fresh river water. This is a promising clean, renewable and non-intermittent sources of energy, but up to now its large scale viability is hampered by the very low efficiency of current harvesting technologies. Therefore the results obtained by the team with boron-nitride nanotubes demonstrate that the exotic behaviour of fluids in the nanoscale regime can further boost the energy conversion by orders of magnitude. This program is now conducted by a start-up company, Sweetch-Energy, which now develop innovative membranes using alternative materials amenable to industrial scale-up. Such fundamental innovations therefore open new avenues to develop out-of-the-box approaches to make osmotic energy a tangible, clean alternative.

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What is the value of the proton charge radius?

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The proton is not a point-like elementary particle, but is composed of three quarks bound together with gluons. Its charge radius r_p , defined as the square root of the second moment of its charge distribution, is in the range 0.8-0.9 fm. A good knowledge of this radius is crucial to test quantum electrodynamics (QED) predictions in simple atomic systems, such as the hydrogen atom. Several methods can be used to determine the proton charge radius but they presently give different results! Our team “*Tests of fundamental interactions and metrology*” (LKB) has recently performed measurements leading to improved determinations of r_p , but the “proton puzzle” remains unsolved.

PROTON RADIUS FROM ELECTRON SCATTERING

Knowledge about r_p can be gained from electron-proton scattering experiments, in which electrons are sent through a thin dihydrogen target and the scattering cross-section is measured. This method requires an extrapolation to zero momentum transfer and a complex data analysis, leading to much debate about the validity of the results. However, ongoing experiments aim to overcome this difficulty.

FROM HYDROGEN SPECTROSCOPY

It can also be accessed by studying the hydrogen atom, composed of a proton and a bound-state electron. The energy levels of hydrogen are well described theoretically, and can be written as the sum of two terms: the first one can be exactly written in terms of the Rydberg constant and other fundamental constants, whereas the second one known as the Lamb shift includes bound-state QED, relativistic contributions, as well finite proton size effects. Indeed, the charge distribution of the proton screens the attractive potential experienced by the electron, at short distance from the nucleus.

The 2S-2P splitting (about 1 GHz) has been measured in the RF domain for a long time, with the aim to test QED predictions. Nowadays, the best determination of this splitting is obtained by comparison of two optical transition frequencies, and high-resolution spectroscopy has reached such a precision that the proton radius has become the limitation to compare QED predictions and experiments. The 1S-2S two-photon transition at 243 nm has been measured in Garching with a relative uncertainty of a few parts in 10^{15} . The measurement of another optical transition allows to derive the Rydberg constant and the proton charge radius, assuming bound-state QED calculations to be exact. The global least-squares adjustment of fundamental constants realized by the CODATA (Committee on Data for Science and Technology, interdisciplinary international committee) relies on such a scheme. Including hydrogen spectroscopy and scattering results in the data collected in 2014, it gave the value $r_p=0.8751(61)$ fm for the proton charge radius (1).

OR SPECTROSCOPY OF EXOTIC ATOMS

To improve the knowledge of the proton radius, an international collaboration called CREMA (Charge Radius Experiment on Muonic Atoms) has been formed, including members of our team. In muonic hydrogen, the electron is replaced by a muon, with a mass about 200 times larger, so that the extension of the muon wavefunction is much smaller and thus more sensitive to the proton charge distribution. The nuclear size effect represents 1.8% of the 2S-2P level splitting of muonic hydrogen, as compared to a proportion of 0.014% in electronic hydrogen.

Direct spectroscopy of the 2S-2P transition of muonic hydrogen at 6 μm was performed at the Paul Scherrer Institute (PSI): by collision of protons on a target, pions are produced which decay in muons, that are decelerated and captured at low energy by a proton. Those muonic hydrogen atoms are finally excited by short laser pulses at 6 μm .

This quite challenging experiment gave a signal in 2009 after 10 years of efforts, but surprisingly shifted from its expected position. The proton radius derived from this experiment was 0.84087(39) fm, an order of magnitude more precise, but about 4% smaller, than the current CODATA-recommended value. This discrepancy, which has become known as the “proton puzzle”, remains unexplained despite an intense theoretical and experimental research activity.

HYDROGEN SPECTROSCOPY AT LKB

Our hydrogen experiment that was used to determine precise values of the Rydberg constant for a long time, is now devoted to the 1S-3S two-photon transition at 205 nm (second best known transition in hydrogen). The goal is to shed light on the “proton puzzle” by measuring this transition frequency at the kHz level. Indeed, the theoretical frequency of this transition is shifted by 7 kHz when calculated with one or the other of the conflicting proton radius values, the 1S-2S frequency being experimentally given.

In 2017, we have obtained a value of the 1S-3S transition frequency with a relative uncertainty of 9×10^{-13} (2). The deduced value of the proton charge radius is 0.877(13) fm, in excellent agreement with the CODATA-recommended value (see figure). But it significantly disagrees with the values derived from muonic hydrogen spectroscopy and from the recently published measurement of the 2S-4P transition frequency measured in Garching (3). Up to now the proton radius puzzle is not closed !

Solving this puzzle needs to further improve ongoing spectroscopic measurements, but also to undertake new experiments: muon-proton scattering at PSI or the study of new transitions in hydrogen, as for example the 1S-4S transition planned in our team.

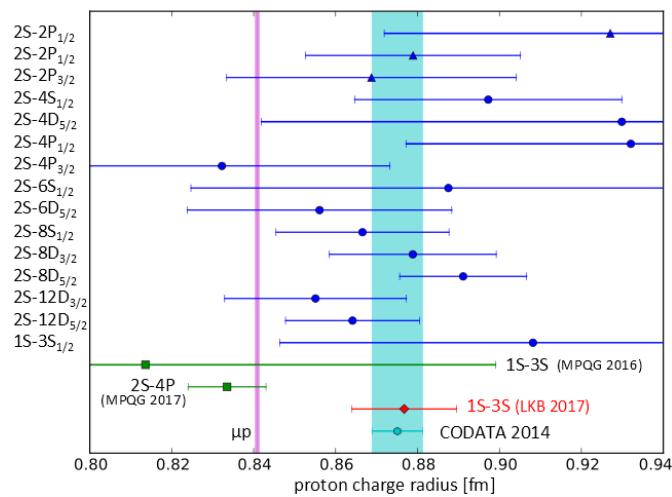


Fig. 1 Proton charge radius values from H spectroscopy, with error bars corresponding to one standard deviation. The pink bar is the value from muonic hydrogen spectroscopy. The light blue bar is the CODATA-2014 recommended value. Green squares are obtained from optical transitions measured in Garching since 2014, and the red diamond is the new 1S-3S measurement at LKB.

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INTERVIEW

David Darson, electronics engineer



Could you explain the kind of support for research you provide?

My work consists in answering all sorts of electronics-related issues, such as signal generation and detection, building prototypes, and offering solutions that do not exist or are not marketed yet. I must provide innovative and original solutions. By listening to experimenters and trying to understand the sort of science they wish to develop, I try to grasp the problems they deal with and therefore conceive solutions to anticipate their needs.

Which innovations have you patented and developed in collaboration with the industrial sector?

In March 2013, I was able to patent the conception, realisation and applications for a new type of very low noise high-precision programmable power supply (NB: one of the two projects for which he was awarded the CNRS Cristal in 2012). It was put to industrial use thanks to a partnership with the Toulouse-based company iTest through a know-how licensing agreement and a research collaboration. I am currently working on an infrared camera that was first developed for an experiment on Terahertz detection to contain both very bright areas and very dark areas on the same image. To do so, I modified the original application of a detector—made in France by NIT—used to record very bright lighting for industrial purposes. I then designed the camera, its casing being designed by an engineer at the laboratory. The camera was built in collaboration with our mechanical engineers. I developed the related software and included new reading modes. For instance, during exposure time, even a very long one, you can now make as many non-destructive readouts as possible. You can therefore literally see the image being made when on pause. These non-destructive readings can be astutely put to use as they offer a new way to reconstruct high dynamic range images that is more efficient than current HDR systems. A patent has been filed and a partnership established with NIT to market the camera.

What are its possible applications?

Besides very high dynamic applications (such as the capture modes of HDR images that are currently available, even to the general public), it offers new perspectives in terms of active and adaptive optics by making use of new reading modes, in astrophysics for the detection of exoplanets, for instance, or even in the medical field. For researchers, this system may improve handling considerably.

Cavity quantum electrodynamics of strongly correlated electronic systems

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Laboratoire Pierre Aigrain (LPA)

The ability to control electronic states at the nanoscale has contributed to our modern understanding of condensed matter. Nanotechnology nowadays enables the study of quantum wells embedded in circuits of an arbitrary complexity. These artificial atoms are often quoted for encoding quantum information-like real atoms. In the last decade these “electron boxes” have also emerged as model systems for condensed matter in which electrons do not behave independently one from the other. In this work, atomic physics is back since we enclose these electron boxes in photon boxes, like in cavity quantum electrodynamics setups celebrated in quantum optics. Using this tool brought from quantum technology, the HQC team develops a probe of electron transfer processes in nanoscale circuits with an ultimate sensitivity and use it in the context of the Physics of impurities which is central to modern condensed matter.

In a free electron gas, electrical conduction is carried by mobile charges.

Its compressibility $\chi = \frac{\partial N}{\partial \mu}$

with N the number of electrons and μ the chemical potential is simply the density of states at the Fermi energy. It is therefore directly linked to the finite conductivity of the system. This explains for example why both the compressibility and the conductivity provide essentially the same piece of information for alkali metals. But what happens in the case of a strongly correlated electronic gas? A prominent situation is that of an electron localized on a single site with strong Coulomb repulsion, coupled to a continuum of electronic states. Besides its apparent simplicity, such a configuration is relevant for understanding different types of strongly correlated gases, ranging from heavy fermions to high T_c superconductors, and therefore a priori relevant for many condensed matter problems. One of the oldest strongly correlated problem being the Kondo effect.

The Kondo effect is a key phenomenon in condensed matter physics because it is a paradigm for strongly electronic systems. In magnetic alloys, it appears as the increase of the resistance of an alloy such as $\text{Cu}_{0.998}\text{Fe}_{0.002}$ at low temperatures. The basic mechanism for it is the antiferromagnetic coupling of a magnetic impurity carrying a spin with the spin of the conduction electrons of the host matrix, as suggested by Kondo in 1964. This coupling has emerged since as a very generic property of a localized electronic state coupled to a continuum. It has been observed in many different systems ranging from an adatom adsorbed on a metallic surface to quantum dots fabricated in two dimensional electron gas, carbon nanotubes or molecules. The possibility to design artificial magnetic impurities-quantum dots- in nanoscale conductors has opened an avenue to the study of the Kondo effect in unusual situations as compared to the original one, and, in particular, in out of equilibrium situations and at high frequency. In the HQC team such quantum dots are designed using carbon nanotubes. The devices are made « in house » using the clean room facility of the physics department, in collaboration with the clean room team.

The HQC team of the LPA has shown that circuit Quantum Electrodynamics architectures can be used to study the internal degrees of freedom of such a many-body phenomenon. They have coupled a quantum dot to a high finesse microwave cavity to measure with an unprecedented sensitivity the dot electronic compressibility i.e. the ability of the dot to accommodate charges. Because it corresponds solely to the charge response of the electronic system, this quantity is not equivalent to the conductance which involves in general other degrees of freedom such as spin. By performing dual conductance/compressibility measurements in the Kondo regime, the charge dynamics of this peculiar mechanism of electron transfer is uncovered. Strikingly, the Kondo resonance, visible in transport measurements, is ‘transparent’ to microwave photons trapped in the high finesse cavity. This reveals that, in such a many body resonance, finite conduction is achieved from a charge frozen by Coulomb interaction.

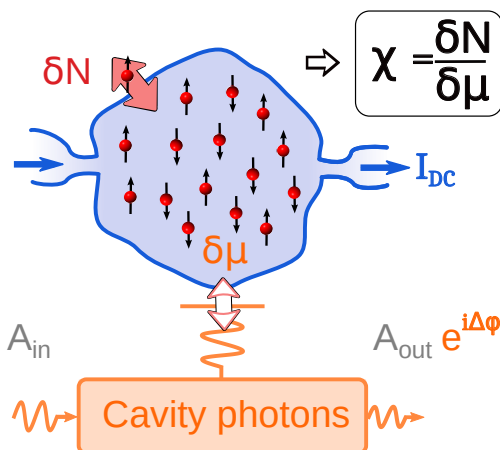


Fig.1 The principle of our measurement setup

This previously elusive freezing of charge dynamics is in stark contrast with the physics of a free electron gas. The setup built by the HQC team highlights the power of circuit quantum electrodynamics architectures to study condensed matter problems. The tools of cavity quantum electrodynamics could be used in other types of mesoscopic circuits with many-body correlations and bring a promising platform to perform quantum simulation of fermion-boson problems.

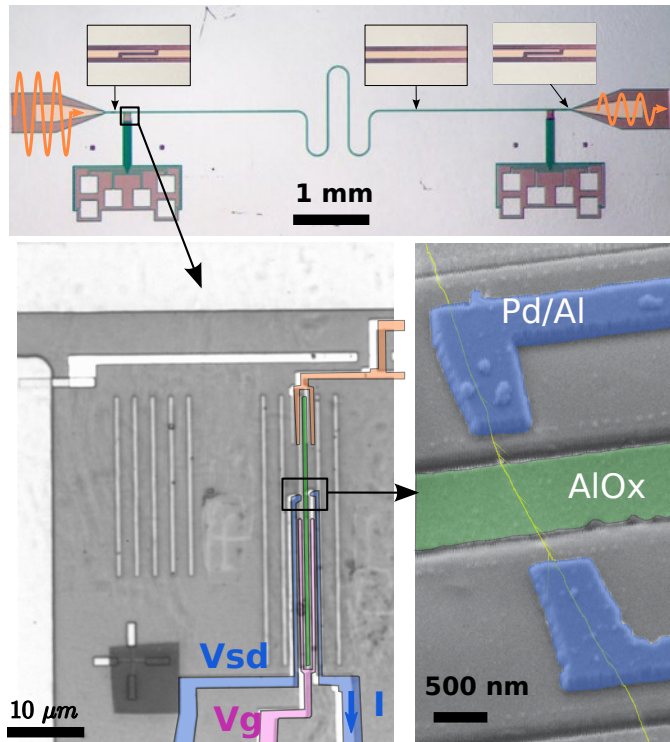


Fig. 2 The device made by the HQC team

The perspectives of this work are numerous since a fruitful analogy can be drawn between the photons stored in the cavity and the phonons in solids, as shown theoretically by the HQC team in collaboration with the theory group of the LPA. In addition, one can also envision to generalize such an architecture in which one would probe directly the photons using superconducting quantum bit technology. If well mastered, such a hybrid architecture would be a solid state quantum simulator of fermion-bosons systems.

INTERVIEW

Nick Kaiser, Professor ENS



Hi Nick, before arriving in Paris, you were working in the Institute of Astronomy at the University of Hawaii. That is a big change! What brought you here?

Well yes, a big change in the style of life and the weather! However, I have had collaborations with cosmologists in the Institut d'Astrophysique de Paris (IAP) for a long time and lots of colleagues are in Europe. Paris is very exciting, a lot of scientific stuff is going on, a lot of seminars to attend, so I already feel at home here. The position at the ENS is a big opportunity for me: the ENS is a prestigious place, with some of the best students in France, and really close to my collaborators in Université Paris Diderot or at the IAP. Moreover, it is challenging to start a new cosmology group in the "Laboratoire de radioastronomie" (LRA) which is historically an astrophysics laboratory.

Can you give us a glimpse of what cosmology is about?

Of course! For my part, I work in physical cosmology, which is to test the existing theory of the evolution of the universe and its structure: the inflation theory. For the last 30 years, cosmologists have had three probes they could use: 1) Galaxy clustering; 2) Fluctuations of the cosmological microwave background (CMB); 3) Probing the presence of dark matter.

And you especially work on dark matter. Where does this concept come from anyway?

When physicists studied the structures of the universe, they realised that extra mass was missing to hold galaxies and galaxy clusters together. From here comes the idea of an invisible component of the universe that we now call "dark matter". Nowadays this dark matter is so well accepted that the questions have shifted from its existence to trying to probe the gravitational laws from its distribution in the universe.

Where do you stand on this dark matter research?

There are several ways to probe dark matter: one can look at the local motion of galaxies (cosmic flows) or one can study the effect of dark matter on light: the gravitational lensing effect, and that's where my research is focused.

How do you see the future at the ENS? More generally the future of your field?

For a start, I will obviously go on with the collaborations I have, for example in the Euclide project. But we will also work on a proposal for a program using clusters of galaxies in diverse ways to test cosmological theories. The next decade is going to be very exciting for cosmologists, because of new instruments with fantastic resolution : the Euclide satellite (ESA) will be launched in 2021, and will be able to probe optical and infrared wavelengths with a very good resolution in one quarter of the sky! Until now, we only had ground measurements that are widely limited by the turbulence of the atmosphere. Another very promising instrument is the construction of the LSST (US mission) wide-field telescope in Chile. This new instruments will be able to test Einstein's theory to a incredible precision, and should be able to tell if our current model with dark matter and dark energy is valid... or if we need to search for something else!

FURTHER ON

M.M. Desjardins et al., Nature 545, 71 (2017)

Characterizing interstellar shocks

Antoine Gusdorf

Laboratoire de Radioastronomie (LRA)

The propagation of shock waves is ubiquitous in the interstellar medium of galaxies. Shock waves indeed represent an important source of energy, and significantly contribute to shape the physical and chemical evolution of galaxies. This is why it is important to study their existence in the Galaxy. We targeted the Cepheus E bipolar outflow associated to an intermediate-mass protostar (whose final mass will be comprised between 3 and 9 solar masses). We observed the emission of carbon monoxide and atomic oxygen lines at THz frequencies with the GREAT receiver onboard the SOFIA telescope. Combined with our prior knowledge of the source, the km.s^{-1} spectral resolution of this instrument allowed us to better understand the nature of the shocks driven by the protostar, structure of the outflow, and the particular chemistry driven by the shocks. In the near future, these observations will also allow us to better constrain the evacuation processes of momentum by the protostar, and the potential acceleration of cosmic rays in the protostellar shocks.

The interstellar medium, that is the medium between the stars in a galaxy, is constantly perturbed by energy injection in three forms: far-UV photons (emitted by massive stars), cosmic rays (particles mostly accelerated in violent events), and mechanical energy (turbulence and shocks). Among these energy injection forms, shocks are of particular importance, as they are ubiquitous in the interstellar medium. Indeed, they accompany the formation of stars in the form of protostellar jets and outflows, the death of certain stars in the form of supernova explosions, and the converging flows of matter intrinsically linked to the Galactic turbulence. The study of shocks is hence crucial to a global understanding of galaxy evolution.

One research axe of the LRA is dedicated to this study along the following questions: what are the physical processes at work? What is the contribution of shocks to the galactic cycle of matter? What is the contribution of shocks to the energetic balance of galaxies? What are the mechanisms allowing forming stars to evacuate angular momentum? Can cosmic rays acceleration take place in these regions? Our research is based on observations, usually performed between the near-infrared and millimeter range (VLT, *Spitzer*, *Herschel*, SOFIA, IRAM-30m telescope, APEX, ALMA and NOEMA...), and on modelling. Our team is involved in the development of a reference code to simulate the propagation of interstellar shock waves: the Paris-Durham model.

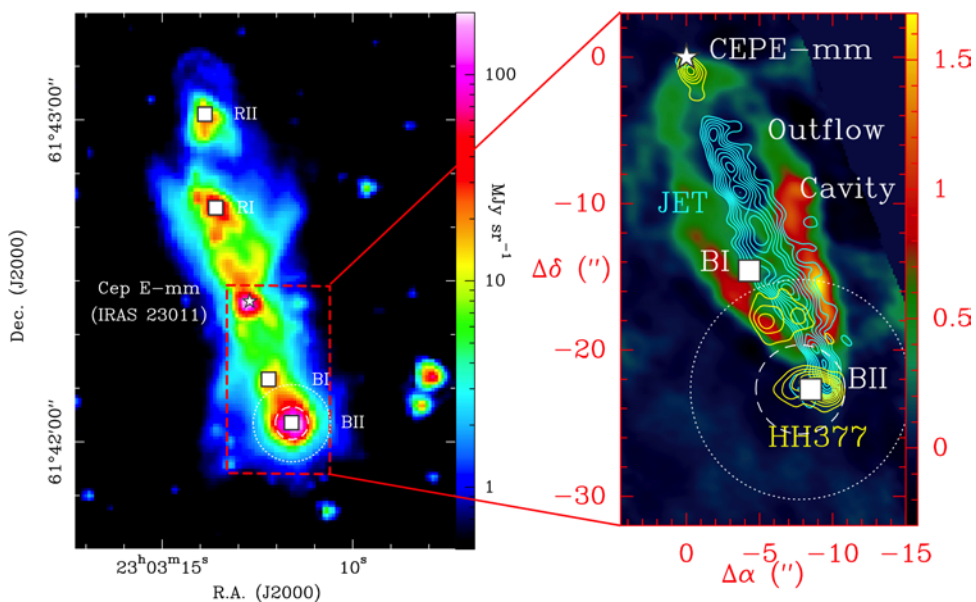


Fig. 1 Left: a finder's chart for the positions of interest in the Cep E protostellar outflow: Spitzer-IRAC band-two ($4.5 \mu\text{m}$) image, showing the knots of bright H₂ emission. Right: zoom on the southern lobe of the outflow showing the spatial components identified in CO (2-1) with the Plateau de Bure Interferometer: the jet (cyan contours), the terminal bow-shock (yellow contours distant from the protostar) and the cavity walls (coloured background). On both panels, bright knots and driving star position are labeled (RI, RII, BI, BII and mm) and respectively marked by white squares and a star symbol. White circles indicate the diffraction-limited SOFIA beams at the frequencies of [O I] 3P1-3P2 at 4.7 THz (smaller circles) and CO (16-15) at 1.8 THz (larger circles) lines.

Here, we studied Cepheus E protostellar outflow, driven by a forming intermediate-mass protostar located at around 730 pc in our Galaxy. Its luminosity is about 100 times that of the Sun, and its final mass will be between 3 and 9 times that of the Sun. The formation of a star is a violent event during which shocks are generated. Indeed, the accretion process is always associated with an ejection process. For reasons linked to angular momentum excess removal, the protostar drives collimated jets extending a few AU to a few pc from the source. The supersonic impact between the jet and the parental cloud generates supersonic (few tens of km.s^{-1}) shock waves in the ambient medium. Large cavities, called ‘bipolar outflows’ (see Fig. 1) are formed.

Our study of the Cepheus E bipolar outflow began in 2012, when we were granted time to observe highly excited CO emission lines with the SOFIA airborne observatory (see Fig. 2). CO is an abundant molecule in the interstellar medium, and such levels are likely to be populated in warm and dense shocked regions. SOFIA is a 2.5m telescope based on a Boeing 747 SP aircraft, with the GREAT receiver operating in the far-infrared (THz) range. The CO (12-11) and (13-12) rotational spectra that we obtained at the Cep E-BII position (see Fig. 1) were looking like the CO (16-15) spectrum shown in Fig. 2, with three velocity components, at high (-140 to -100 km.s^{-1}), intermediate (-100 to -50 km.s^{-1}) and low velocity (from -50 to -10 km.s^{-1}). We derived the physical conditions associated with these components, and requested further observations to better understand their origin.

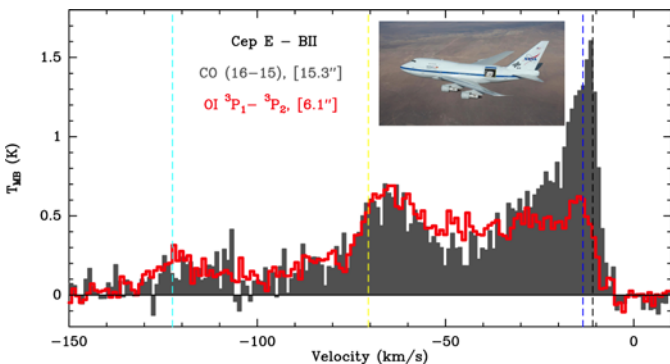


Fig. 2 CO (16-15) (grey histograms) and [OI] 3P1-3P2 (red line) observations obtained in Cep E-BII with the GREAT receiver onboard the SOFIA telescope. The vertical dashed lines represent Cep E's velocity (in black), and the central value for the velocity components mapped in Figure 1-right: the jet (cyan, -122.5 km.s^{-1}), the terminal bow-shock (yellow, -70.5 km.s^{-1}), and the cavity walls (blue, -13.5 km.s^{-1}). The inset shows the SOFIA telescope in action.

In 2015, we published maps of the CO (2-1) emission performed with the Plateau de Bure Interferometer. Their excellent spatial (see the right-hand side panel of Fig. 1) and spectral resolution allowed us to understand that the high-velocity gas was tracing the primarily jet launched by the protostar, that the intermediate-velocity gas corresponds to the bow-shock created by the impact of its apex on the surrounding medium, and that the low-velocity gas is tracing the cavity walls of the outflow carved by the jet. Additional CO observations with the *Herschel*, IRAM-30m, and *James Clerk Maxwell* telescopes, were used to specify the physical conditions in each of the velocity components, measure the momentum and mechanical energy they inject in the medium, and model the formation of the outflow system. We also constrained the jet shock conditions by means of the Paris-Durham model, showing that the jet can be modelled by a non-stationary shock propagating at 20-25 km.s^{-1} .

Finally, in 2017, we used pointed observations of the [OI] 3P_1 - 3P_2 line emission with SOFIA-GREAT (see Fig. 2) to measure the abundance of atomic oxygen in each of the velocity components. This measurement is of particular importance to our understanding of shock physics and chemistry, as oxygen traces specific processes. Here, an excess of [OI] emission could be the sign of dissociation of H_2O and/or CO, either by collisions or by photons, occurring within the shock layer. This could mean that we underestimated either the velocity of the shock and/or the role of the protostellar radiation field. In the case of the jet shock, we found that the oxygen-to-CO ratio could be indicative of the generation of far-UV photons by the shock itself.

We obtained more observing time to verify this possibility and pursue our characterization of this protostellar outflow. The observations will be carried out in 2018 and will generate the first full velocity-resolved map of an outflow in the [OI] 3P1-3P2 transition, only made possible by the advent of SOFIA-GREAT. Such observations are crucial to address the questions listed above, and in particular to progress in our understanding of chemistry.

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[A.I. Gómez-Ruiz, A. Gusdorf, S. Leurini et al. A&A, 542 \(2012\)](#)

Fluctuations of electrical conductivity: a new source for astrophysical magnetic fields

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Non-linear Physics
Laboratoire de Physique Statistique (LPS)

Most of the astrophysical magnetic fields in the universe are believed to be generated by the turbulent motions of an electrically conducting fluid: the molten iron in the Earth's core, the ionized gas of our galaxy or the plasma of the stars: this is called the dynamo theory. Until now, it was believed that this instability required flows of complicated geometry. We have shown that such a complicated flow is not necessary if the electrical conductivity of the fluid is not assumed to be uniform. In that case, a new induction mechanism takes place so that planar flows can create a dynamo, which is impossible if the conductivity is uniform. This result provides an explanation for the spatial structure of the magnetic field of the iced giants (Neptune and Uranus) which magnetic field has a strong equatorial dipole component.

Most astrophysical objects have a magnetic field. It is the physicist Joseph Larmor who first, in 1919, identified the origin of these magnetic fields: The very turbulent motions of the conducting fluid (the liquid iron in the Earth core or the plasma in the solar convective zone) create magnetic field from the kinetic energy of the fluid; it is the dynamo instability. Despite nearly a hundred years of research, several questions remain unsolved especially because simple solutions to the problem do not exist. Indeed for a fluid whose physical properties are uniform, there are theorems (called «anti-dynamo») proving that simple flows such as planar flows cannot create a magnetic field.

The vast majority of existing studies assume that the electrical conductivity of fluids is uniform. In many situations, it is safe to assume that the conductivity do not change too abruptly in space and time. But in astrophysics, one may expect to observe strong fluctuations of the electrical conductivity due to the huge temperature variations or the inhomogeneities of the fluids encountered in galaxies, stars and planets.

By studying the effect of spatial variations in electrical conductivity, we have identified a new induction mechanism that allows to obtain dynamo instability in flows much simpler than those considered until now, and forbidden by classical theory. For instance, we discovered that planar flows can generate a dynamo, because anti-dynamo theorems do not apply in presence of conductivity variations.

A numerical modeling of the interior of planets and stars shows that this new effect generates a dipolar magnetic field transverse to the axis of rotation of the object. This mechanism thus provides a simple explanation for the spatial structure of the magnetic field of ice giants Uranus and Neptune that have a strong transverse component.

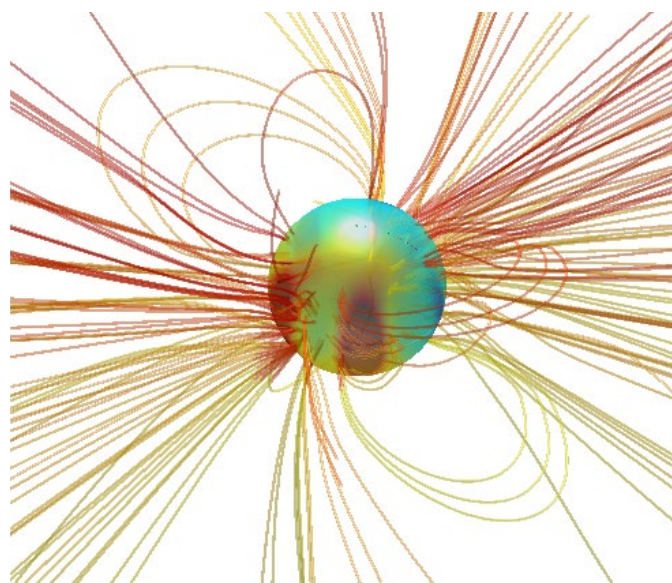


Fig. 1 This picture shows the dipole field generated at the core-mantle boundary in one of our geodynamo simulations. In this model, fluctuations of the electrical conductivity of the fluid, due to variations of temperature in the core for instance, act as a new source for astrophysical magnetic fields.

The non-linear physics group involves 4 permanent researchers (A. Alexakis, C. Gissinger, F. Petrelis, S. Fauve) and focuses on non-linear and statistical physics, mostly within the framework of fluid mechanics. In particular, the group's research combines laboratory experiments, theory and numerical simulations to study various phenomena such as flow instabilities, dynamical systems, turbulence, or magnetohydrodynamics, i.e. the study of the dynamics of electrically conducting fluids.

FURTHER ON

F. Pétrélis et al., *Phys. Rev. Lett.* 116 161102 (2016)

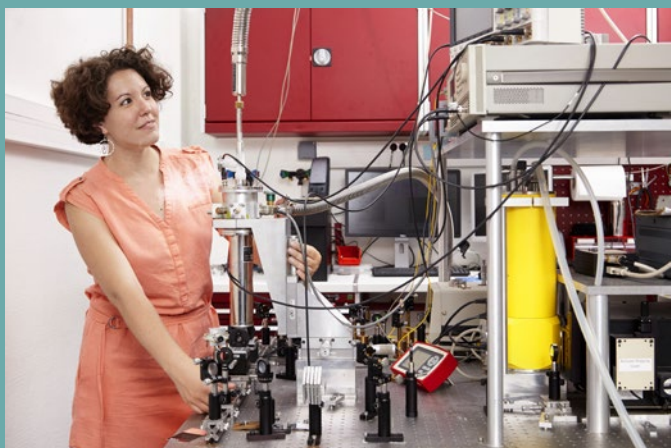
PORTRAITS

Two ENS PhD students got the l'Oréal-UNESCO grant for Women in Science

Sophie Marbach and Sarah Houver witness their PhD experience and their 2017 grant

Sarah Houver

Ultrafast THz Spectroscopy (LPA)



I did my PhD within the Laboratoire Pierre Aigrain from ENS Physics Department, from 2013 to 2017, in the Ultrafast Terahertz Spectroscopy team. Carrying my researches in this environment, supported by several engineering services and having the opportunity to discuss with many brilliant scientists was a great boost to my work.

I focused my research on a new laser source emitting light in the far infrared range: the Quantum Cascade Laser. I used this very compact source, composed of nanometric semiconductor layers, to study nonlinear optical phenomena between near infrared and far infrared light, directly into the compact device. My research opens new understanding of these phenomena and new possibilities for telecommunication applications, for example.

The "l'Oréal-UNESCO Fellowship For Women in Science" honors promising young female researchers for their work as PhD candidates or post-doc. The grant brings additional support for these young women throughout their scientific careers. It was a great honor for me to receive this fellowship. It brought me more visibility and gave me the opportunity to extend my network by visiting laboratories abroad and attend several international conferences.

Last but not least, it had the opportunity to communicate to high school students about my interest for science and my personal career to inspire both boys and girls towards all kinds of science and make them consider scientists and science world without biases, for richer discoveries in the future.

Sophie Marbach

Micromégas (LPS)



I am currently finishing my PhD in fluidics at the ENS Physics department. At very small scales –where the fluid flowing is only constituted of a few molecules– numerous curious and thrilling effects occur and are still to be explored. They can be for example harvested to improve filtration and desalination systems.

The l'Oréal-UNESCO grant for Women in Science is a prestigious recognition, delivered by an independent academic jury, for the work I have performed during my PhD. Working at the ENS was an incredible opportunity to improve the quality and the impact of the Science that I was conducting. The school is located in a swarm of outstanding scientists and great facilities, and I had the chance to build many interactions and a few fruitful collaborations there.

The l'Oréal-UNESCO prize is a great stepping-stone for my career as a scientist, and brought me more self-confidence. In a context where I do not encounter so many high profile women scientists, it is priceless to be encouraged to continue on this path. On top of the training I received at the foundation, I also went to meet and talk with numerous highschool students, male and female, to encourage them to engage in Science. Love of Science is already a key to being good at it, and I encourage any woman who may consider Science to persevere. Humanity should not be deprived of half of its intellectual strength!

Why is it hard to solve the 3D Ising model? Conformal bootstrap perspective

Slava Rychkov

Laboratoire de Physique Théorique (LPT)

The conformal bootstrap has recently provided the most precise data about the critical point of the 3D Ising model, relevant for describing the Curie point of ferromagnets and many other second-order phase transitions. These data also reveal why traditional perturbative approaches had had only limited success when studying this model.

The Ising model describes statistical mechanics of classical spins $S_i = \pm 1$ assigned to the vertices of a cubic lattice in D dimensions and experiencing a nearest-neighbor ferromagnetic interaction. The most interesting cases are $D=2,3$, because in these dimensions the model has a continuous order/disorder phase transition with non-mean-field critical exponents. The study of this phase transition is an old quest in physics. The story we will tell is one facet of this quest.

Historically, the Ising critical point was first understood in $D=2$, via Onsager's exact solution of the lattice model, and next in $D=2,3$ via Wilson's renormalization group (RG). From modern perspective, physics of the critical point is described by conformal field theory (CFT) -- a rigid algebraic structure imposing tight consistency rules on how long-range critical fluctuations of different types interact with each other. These "CFT equations" provide an alternative to the RG.

In $D=2$, the CFT equations turns out to be exactly solvable (Belavin, Polyakov, Zamolodchikov, 1984), but in $D=3$ all attempts to find an analytic solution have so far not been successful. In spite of this difficulty, efficient algorithms have been developed in recent years to analyze the CFT equations numerically on a computer -- the approach known as "the conformal bootstrap".

The conformal bootstrap describes the critical point via a list of local operators $O_i(x), x \in \mathbb{R}^D$, characterized by their scaling dimension $\Delta_i > 0$ and tensor rank (spin) $\ell_i = 0, 1, 2, \dots$. There are infinitely many such operators, with larger and larger dimensions, but the equations converge when infinite sums are truncated below some cutoff. Practical computations typically deal with hundreds of operators. A further ingredient is the "operator product expansion" (OPE) -- the ability to expand the product of any two nearby operators $O_i(x)$ and $O_j(y)$ as an infinite series $\sum_k c_{ijk} O_k$ of operators inserted at the midpoint $(x+y)/2$. Some coordinate dependent factors fixed by conformal symmetry are left implicit in this equation; we don't describe them here for the sake of brevity (see [2] for further details). The important part are the numerical OPE coefficients c_{ijk} , playing the role of coupling constants in this approach. The conformal bootstrap solves for the dimensions Δ_i and the OPE coefficients c_{ijk} by imposing the

consistency condition that doing OPE for a group of four operators pairing them in all possible ways should give the same result.

The conformal bootstrap has greatly increased our knowledge of the critical 3D Ising model. For example, the leading critical exponents $\eta = 0.036296(2)$ and $\nu = 0.629971(4)$ are now known several orders of magnitude better than what has been achieved in the previous 40 years with direct Monte-Carlo simulations or with the RG methods. The theoretical precision is now better than the experimental precision, which should stimulate the experimentalists to come up with better techniques to measure these numbers in the lab and check their universality. Notice that according to Wilson's RG theory, these critical exponents are universal parameters of Nature, no less fundamental than π or e or $\zeta(3)$. But we don't know much about these numbers apart from the first few digits, not even if they are rational or irrational. Any advance in understanding these numbers is a priori important.

Perhaps even more impressively, the critical correlation function of four Ising spins $\langle S_1 S_2 S_3 S_4 \rangle$ has been determined using the bootstrap with permille accuracy for arbitrary positions of the four spins $S_i = S(x_i)$. This correlation function encodes in a nontrivial way information about infinitely many types of critical fluctuations which couple to the fluctuations of spin (in CFT parlance, these are primary operators which appear in the OPE $S \times S$).

One well-known feature of the critical 3D Ising model is the smallness of the anomalous dimension of the spin field, the corresponding critical exponent η being only a few percent. This is sometimes taken as a hint that the model is secretly nearly free, and should be amenable to perturbative calculations, if only we knew how to do this. One well-known proposal for such a scheme is the $4-\epsilon$ expansion of Wilson and Fisher, but it is only asymptotic and provides mediocre accuracy even after elaborate resummations.

The notion of being "nearly free" was used in the previous paragraph at an intuitive level, but it can be made precise as follows. Free theories are characterized by the property that their correlation functions are gaussian, fully fixed from the covariance. If spin were a gaussian variable, its four-point

function would take a fully factorized (disconnected) form. In general, consider the non-gaussianity ratio Q between the full four-point function and its disconnected part:

$$Q = \frac{\langle S_1 S_2 S_3 S_4 \rangle}{\langle S_1 S_2 \rangle \langle S_3 S_4 \rangle + \langle S_1 S_3 \rangle \langle S_2 S_4 \rangle + \langle S_1 S_4 \rangle \langle S_2 S_3 \rangle}.$$

If the theory is gaussian, then Q is identically equal to 1, otherwise it's a function of two real conformal invariants u, v which can be constructed out of the positions of the four spins. We can then say that the theory is "nearly free" if Q deviates only slightly from 1. With this definition, is the 3D Ising model nearly free?

Until recently, the only result about Q in the 3D Ising model was a rigorous inequality $1/3 \leq Q \leq 1$ due to Lebowitz (1974) and Aizenman (1982). Now, thanks to the conformal bootstrap, the functional dependence of Q can be determined (cf. Fig. 1). These calculations reveal that Q is consistent with the Lebowitz-Aizenman inequality, varying between 1 and a lower bound of about 0.7. The fact that Q deviates so much from 1 is surprising, as it shows that the 3D Ising model is capable of exhibiting significant non-gaussianity in spite of small η . Clearly, the critical 3D Ising model is far from being free, and this provides an explanation why the old perturbative approaches had hard time to make precise predictions about it.

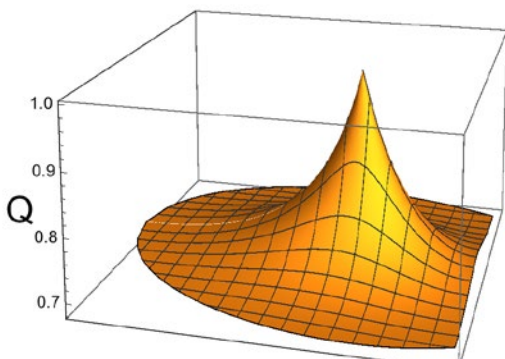


Fig. 1 Q in the critical 3d Ising (vertical axis), plotted as a function of the conformal invariants u, v (horizontal axes, see [1] for details).

FURTHER ON

- [1] S. Rychkov et al., "SciPost Phys. 2 (2017) no.1, 001
- [2] D. Poland and D. Simmons-Duffin, Nat. Phys. 12 (2016) no.6, 535-539

PORTRAITS

Hubert Raguet



For twenty years, Hubert Raguet has been a science photo-reporter for press magazines and for the communication services of research institutions such as the CNRS or the INRIA. He has also worked for the ENS Department of Physics.

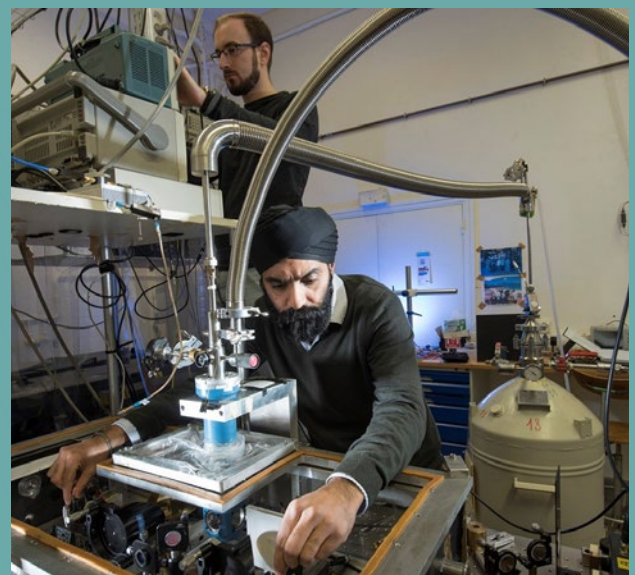
His work mainly highlights scientific experiments and discoveries. His photographs are almost always staged as they reconstruct actions or situations to portray them in a positive and meaningful light.

But when reporting, Hubert often witnessed scenes that offer a sensitive insight into the reality of working conditions in research laboratories. However, he was unable to capture them.

Since September 2017, he has therefore embarked on a long-term photographic project at the Department of Physics in collaboration with its communication services and some research teams there. The idea is to shed a new light on research in the making and on its pace.

This visual testimony will show how and why men and women dedicate their lives to research and all that it involves: commitment, efforts, contradictory feelings, more or less exhilarating tasks, ambition, discouragement and perseverance. Hubert manages to capture all this through gestures, postures and circumstances that illustrate the life of those who devote their lives to research and, day by day, put the pieces of the "puzzle" together.

He has exhibit his work in June 2018 in the entrance of the Lhomond and Erasme buildings.



Postsynaptic domains as diffusion-controlled structures

Vincent Hakim

Complex networks and cognitive systems
Laboratoire de Physique Statistique (LPS)

Synapses are key biological structures. Synaptic dysfunction is implicated in many neuropsychiatric disorders and synapses are the targets of most drugs and medications. As such, synapses have been the focus of numerous biological studies including detailed biophysical investigations. In a recent work, we have built upon this knowledge to propose that postsynaptic domains - molecular structures on the receiving side of the synapse, are formed and maintained by a dynamic balance between lateral diffusion of molecular components along the cell membrane and their turnover at the cell surface. Our theoretical proposal links different measured quantities such as the size of the postsynaptic domains and the diffusion properties of neurotransmitter receptors on the neuron membrane. It also offers a different perspective on the origin of synaptic domain properties, such as their size fluctuations in time or their shapes.

Neurons, like other cells, are enclosed by an external membrane. This lipid bilayer electrically insulates the cell and allows it to be negatively polarized (few tens of mV) with respect to the exterior medium. The membrane dynamics of neurons can amplify membrane potential depolarisations and produce large positive potential excursions of short (a few ms) duration. These so-called action potentials are the basic way by which information is carried and processed by neurons. Information can also be transmitted from one neuron to another through a chemical synapse. An action potential reaching the presynaptic side of a synapse leads to the release of neurotransmitter molecules. After diffusion across the synaptic cleft, these produce a change of the postsynaptic neuron membrane potential by binding to receptors (transmembrane proteins), as sketched in Fig. 1. This potential change can be depolarizing for excitatory synapses or hyperpolarizing for inhibitory ones. The amplitude of the membrane potential change, called the synapse strength, is related to the number of receptors at the synapse, itself proportional to the size of the postsynaptic domain. This has motivated several teams to adopt biophysical methods such as single particle tracking, fluorescence recovery after photobleaching (FRAP) and superresolution microscopy as shown in Fig. 2, and precisely measure the molecule numbers and dynamics of some essential components of postsynaptic domains.

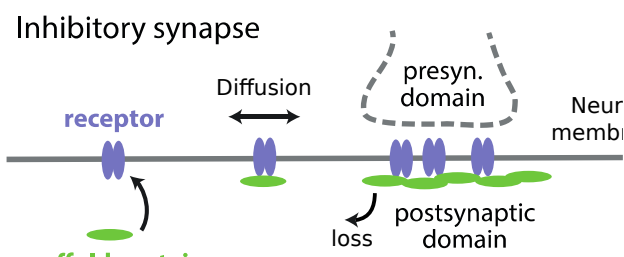


Fig. 1 Sketch of a synapse. The presynaptic terminal (dashed grey line) is the site of neurotransmitter release by the presynaptic neuron. On the postsynaptic side, receptors are shown in dark blue and scaffolding proteins in green.

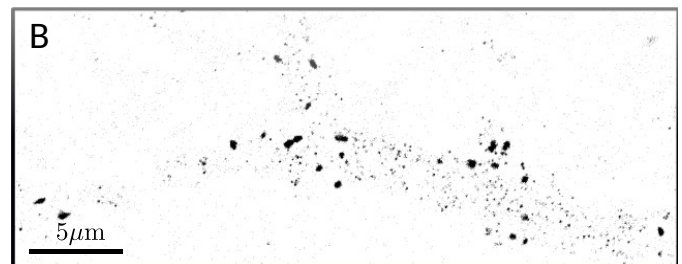


Fig. 2 Pointillist representation of an image of gephyrin clusters in a neuron, acquired by photoactivated localization microscopy (PALM). Each point represents a single detection. © Image: P. Rodriguez

The team led by Antoine Triller at the Institut de Biologie de l'ENS (IBENS) focuses on inhibitory synapses. Two essential components of which are the gephyrin scaffolding proteins and the inhibitory neurotransmitter receptors, the glycine (GlyR) or GABA receptors. One essential and striking finding is that synaptic components are very dynamic: Neurotransmitter receptors have been observed to diffuse on the neuron membrane in and out of synapses on a ten-second time scale. Even scaffolding proteins have been found to only have a half hour residence time at the synapse.

In collaboration with Triller's group, these and other results have led us to investigate theoretically the biophysical formation and maintenance of synaptic domains. Our analysis supports the surprising view that most of the scaffolding proteins are inserted extrasynaptically in the neuron membrane, diffuse under the membrane, bound to receptors and aggregate with postsynaptic domains upon random encounters. Postsynaptic domains result from a balance between growth and loss. Domain growth depends on the aggregation of diffusing scaffolding proteins and is balanced by scaffolding turnover in the domain. The analysis links previously unrelated quantities such as receptor diffusion in the cell membrane, scaffolding protein residence time at synapses and postsynaptic domain sizes. It has led us to predict a distribution of gephyrin

aggregates diffusing outside synapses which is consistent with newly reported measurements. It also suggests large and specific temporal fluctuations of synaptic domain sizes (see Fig. 3) that remain to be measured. More generally, the proposed picture offers a view of synapses as diffusion-controlled structures outside thermodynamic equilibrium. This links them, in an unexpected way, to other complex structures growing by diffusion that have been studied at the LPS, like snowflakes in undercooled water or crystals in supersaturated solutions.

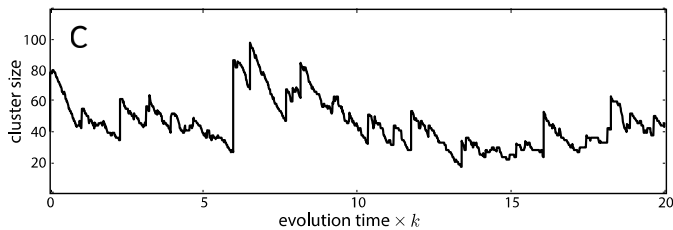


Fig. 3 Simulated evolution of a postsynaptic domain size. Large upward jumps arise from the aggregation of diffusing clusters on the considered domain while subsequent size diminution is due to scaffolding protein turnover. One can see that the process is not invariant by time reversal which is a proof of its non-equilibrium nature.

THE TEAM AND ITS SCIENTIFIC INTERESTS

During the last forty years, statistical physics has expanded from molecular components of gases and liquids to the analysis of the collective properties of large assemblies in which the individual constituents can be virtually anything, for instance, cells in a tissue, birds in a flock, people in a crowd, cars on a road or nodes in the Internet. The members of the team « Complex networks and cognitive systems » study these different aspects with a particular focus on neural systems and quantitative biology.



PARABOLE

Each year, the Parabole Project, which is subsidized by the CNES (National Centre for Space Studies), offers three French student teams the opportunity to experiment in microgravity. Students whose applications have been successful are then responsible for conducting their experiment from its theoretical conception all the way to its realisation on a parabolic aircraft flight.

We learned about the project from the ENS Head of Studies and with the help of the Department of Physics, we were able to apply with a proposal that was selected for the flights scheduled for fall 2017. For six months, we worked under the supervision of two researchers, Frédéric Chevy and Christophe Gissingier, as well as research engineer Nabil Garroum, whose help proved particularly valuable when it came to technical aspects. The purchase of the equipment was generously financed by DELPHY, an association of former ENS physicists.

In October 2017, we were finally able to board the CNES Zero-G aircraft to conduct our experiment: to make water droplets bounce in microgravity! No one had ever tested the mechanical properties of water droplets in a low-speed and large-radius regime, which we were able to obtain in a quasi zero-gravity environment in the reference frame of an aircraft almost going into free fall. We haven't yet finished analysing the high-speed data acquisition videos, but we are very confident in the quality of the results. Even though none of us plans to do a PhD in fluid mechanics, the Parabole Project has provided us with a new, professional outlook on the world of research, in particular by making us aware of high levels of safety requirements when experimenting in the aircraft. Needless to say that we also very much enjoyed floating like astronauts in the ISS, an experience we will never forget!

Andréane Bourges, Valentin Crépel and Lucas Pinol

Valentin and Lucas are to start their PhD next year, in condensed matter and in cosmology. As for Andréane, she is doing an internship with the Corps des Mines on strategy and innovation at the CNES.

FURTHER ON

J. Ranft et al., PLoS Comput Biol 13 (4): e1005516 (2017)

Following the energy trail in the environment of high-redshift starburst galaxies

Édith Falgarone, Benjamin Godard & al.

Laboratoire de Radioastronomie (LRA)

The growth of galaxies in the early universe is largely governed by the conversion of massive gas reservoirs into stars. The gas feeding of star-forming galaxies generates intense turbulence that acts as an energy buffer over timescales that are essentially unknown. The unique chemical properties of the CH^+ cation make it a robust tracer of turbulent dissipation. The recent discovery by the Herschel satellite of very bright gravitationally lensed galaxies at high redshift, combined with the outstanding sensitivity and resolution power of the ALMA interferometer, has opened the possibility of absorption spectroscopy against the dust thermal emission of these galaxies. The detections of the CH^+ line in absorption and in emission unveil large turbulent reservoirs of diffuse molecular gas around these galaxies. This discovery is a major step forward in our understanding of how gas accretion is regulated around the most intense starburst galaxies in the early universe: it shows that galactic feedback, mediated jointly by turbulence and gravity, extends the starburst phase instead of quenching it.

Our understanding of the growth of galaxies in the early Universe still faces major issues: how galaxies accrete their gas to form stars and why is star formation such an inefficient process, even at its peak at redshifts $z \sim 1-3$. While mechanical feedback from stellar- or active galactic nuclei-driven outflows and radiation pressure do contribute to the self-regulation of cosmic star formation, the fraction of gravitational energy from high accretion rates stored in turbulent motions is still unknown. The alternative, i.e. loss of this energy by radiation, leads to the well-known 'overcooling problem'.

The results reported below build upon three independent backgrounds.

One molecular species, CH^+ , called methylidyne, is now known to be a remarkable tracer of turbulent dissipation. Its formation is so highly endoenergetic that a supra-thermal source of energy is required: although CH^+ was one of the first three molecules ever discovered in interstellar space in the early 1940's, its large observed abundances have long been a mystery to molecular astrophysicists. Not only does it require supra-thermal energy to form, but its extreme reactivity also provides it with an extremely short lifetime. CH^+ is now understood to form in shock waves and regions of intense turbulent dissipation, such as the environments of strong coherent vortices in turbulence. By highlighting the tiny regions where turbulence dissipates, CH^+ unveils the otherwise invisible tenuous medium in which it forms, as does the fluorescent plankton in a dark turbulent sea at night.

Our vision of the remote universe has been recently enlarged by the sub-millimeter satellite *Herschel* with the discovery of a population of starburst galaxies, invisible at other wavelengths. These are tiny but already massive dust-enshrouded embryos of galaxies, at the zenith of cosmic star-formation history, forming stars at rates 200 to 1000 times the average rate of the Milky Way today. Their discovery was made possible because

they are all gravitationally lensed, with magnification factors up to 40. These sub-millimeter sources have been used as beacons to probe their diffuse environments with absorption spectroscopy (Fig. 1).

The outstanding capabilities of the Atacama Large Millimeter Array (ALMA), in angular resolution, sensitivity and spectral resolution, have allowed, for the first time, the detection of the fundamental rotational $\text{CH}^+(J=1-0)$ line in all the redshift starburst galaxies targeted so far. While the carbon monoxide, CO, is the ubiquitous tracer of the molecular universe, even at high redshift, it is remarkable that a very rare species like CH^+ , about 10000 times less abundant than CO, be detected at all in the environment of high redshift galaxies. Moreover, the CH^+ line is detected in absorption and in emission in almost all cases with different velocity patterns. The CH^+ emission lines are extremely broad, several times broader than the CO lines (Figure 2). They reveal dense shock waves powered by hot, fast galactic winds driven by either the powerful on-going star formation in these systems, or active galactic nuclei. The CH^+ absorption lines are also broad and either red- or blue-shifted with respect to the emission. They unveil large amounts of diffuse, highly turbulent, molecular gas in which CH^+ formation is activated by turbulent dissipation.

Thus, the power (and beauty) of high resolution molecular spectroscopy lies in the fact that the mere analysis of CH^+ line shapes (widths, intensity, depth of the absorption), in conjunction with known quantities regarding these galaxies, leads us to ground-breaking statements: the turbulent haloes of diffuse gas are gravitationally bound to the galaxy embryos, they extend far away from these embryos, the high-velocity galactic winds alone cannot replenish the mass of the turbulent haloes, eventually drained by star formation.

An additional source of baryons is required to feed the starburst galaxies over their lifetime. It could be galaxy mergers but

more likely, the elusive cold streams pervading the dark matter potential wells, predicted by theory to be feeding galaxies at high redshifts. Regardless of its origin, turbulence appears to be a key process in the regulation of accretion in the most intense starburst galaxies in the early universe.

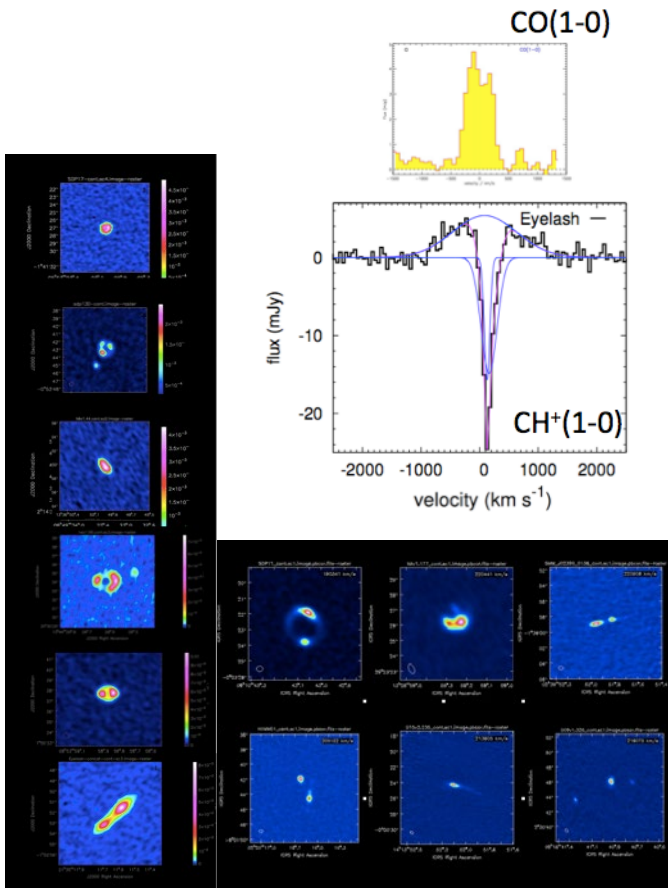


Fig.1 CO($J=1-0$) and CH+($J=1-0$) spectra of one of the starburst galaxies, the Cosmic Eyelash. The x-axis is the velocity of the molecules with respect to that of the centre of gravity of the galaxy. The width of the line, in emission as in absorption, is therefore a measure of the velocity dispersion of the molecules. The comparison of the CO and CH+ linewidths is a critical input to unravel the physics of these systems.

Fig.2 Continuum images of 12 of the ALMA targeted starburst galaxies. The continuum emission is that of the dust thermal emission at 350 micron in the rest frame of the galaxies. All the images are multiple: most are multiple images due to gravitational lensing by an intervening galaxy (or galaxy cluster) of the background starburst galaxies. In two of the fields, the two galaxies are real pairs of galaxies. Note the almost perfect Einstein ring in one of them.

INTERVIEW

Badih Assaf, JRC at the ENS Physics department

Hi Badih, you are one of the few post-docs in the Physics' department to have a Junior Research Chair. Can you explain what is the JRC program?

My work consists in answering all sorts of electronics-related issues, such as signal generation and detection, building prototypes, and offering solutions that do not exist or are not marketed yet. I must provide innovative and original solutions. By listening to experimenters and trying to understand the sort of science they wish to develop, I try to grasp the problems they deal with and therefore conceive solutions to anticipate their needs.

Why have you been interested in this position?

I got interested in this program for three reasons. Firstly, it provides a great amount of autonomy for researchers to implement their own ideas. Secondly, the award includes a generous travel budget, a small budget to fund instrumentation for experimentalists, and a yearly budget that allows the JRC to recruit short-term research assistants. These allow researchers to also have logistic autonomy when launching their program. Thirdly, contrary to a 'classical' postdoctoral fellow, a JRC is always expected to maintain a teaching activity that allows him to remain close to students and in touch with how his own achievements in research can reflect on the evolution of fundamental concepts in physics and their integration in academic programs.

What is your research about? How does the JRC program help you in it?

The JRC award allowed me to establish a solid and recognized research program at ENS aimed at experimentally studying topological phases of matter. These novel material systems are essential for the development of next-generation spin-based and quantum computing devices. My expertise combines the use of optical and electrical tools to study the fundamental properties of these new materials when subjected to strong magnetic fields (as high as 60T). The JRC award allowed me to acquire, maintain and run, several new experimental tools. Most notably, it supported the set-up of a new chemical vapor deposition furnace that is currently being used to synthesize those materials, in-house. The award also allows me to travel to different European research facilities that are specialized in experimental techniques at very high magnetic fields, such as the Helmholtz-Zentrum at Dresden-Rossendorf and the Laboratoire National des Champs Magnetiques Intenses in Grenoble. Work performed in our lab as well as at these facilities has so far resulted in several achievements. The most important among them is the discovery of new electrical transport signatures of that allow scientists to identify non-trivial topological materials. This was recently published in *Physical Review Letters*. [PRL 119 106602 (2017)]. In the future, we will pursue work on topological materials in the quantum confined limit and continue to study the fundamental properties of the recently predicted 3D Dirac semimetals.

FURTHER ON

Falgarone et al., *Nature* 548 430 (2017)

