

SPG MITTEILUNGEN COMMUNICATIONS DE LA SSP



**Annual Meeting of the
SWISS PHYSICAL SOCIETY**

23 - 25 August 2016
Università della Svizzera italiana, Lugano

Call for Abstracts: Submission Deadline 30 April 2016

More information on page 4



LYL 2015 (1): EPFL held a special workshop on light for children. Review on p. 43.

Photo: ©: EPFL - Murielle Gerber



Energy Efficiency by Warm Water cooling - Super-MUC Petascale Cluster at the Leibniz Supercomputing Center. See p. 12. Photo: ©: IBM Research - Zurich



LYL 2015 (2): Auch in der Kunst spielt Licht eine wichtige Rolle. Ein Beispiel stellen wir auf S. 45 vor. Photo: ©: Uwe Niklas

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Swiss Academy of Engineering Sciences

Editorial

Physics by simple concepts

Gian Michele Graf, *Theoretische Physik, ETH Zürich*

In recent issues of these *SPG Mitteilungen* some of my fellow members of the board of the Society have taken turns in expressing their views on physics. More often than not these considerations did not avoid - and rightly so - some of the more pressing questions of our times like sustainable energy supply, climate change, or the quest for novel materials, just to name a few. It is now my turn as a theoretical (in fact: mathematical) physicist to butt in. I would like to raise some appreciation for, or at least some toleration of the idea that still today physics may be pursued for its own sake. As I experienced on occasions that idea seems to face resistance from some of our contemporaries who do not practice science and sometimes even from some who do. Before attempting to dispel that resistance, let me consent that it may not be totally unfounded. Never more than in the last few decades the theoretical efforts striving for the unification of physics, and among them string theory, have been characterized by such a huge disproportion between the intellectual verve on the one hand and the elusive confrontation with experiment on the other. For sure, some disproportion is necessary for any theory in its making, if it is to bring about a physical revolution. While that criterion is clearly not sufficient, it is harder to say what it takes to justify its continued pursuit. In fact, on the one side, string theory has benefitted mathematics by being an undisputed and inexhaustible source of inspiration to areas like number theory, group theory, and differential as well as algebraic geometry; whereas on the physics side there is more ambivalence: In search of a firm physical interpretation string theory underwent several revolutions, though without always becoming more committing or less allegorical. For instance, one of them was called M-theory by Witten because "M stands for magic, mystery or membrane, according to taste." Such statements are bound to raise awe as well as perplexity among the wide and fragmented community of physicists.

But let me get closer to my point. Some of the groundbreaking changes in physics, like relativity and quantum mechanics, were brought about by the work of rather mathematically minded theoreticians. Their insights are rooted in deep, yet in hindsight fairly simple concepts, including symmetry in general and gauge invariance in particular. The main message here is that all this is not just remote history, but alive and well. In fact the biggest new development in solid state physics during the last 10 years is an outgrowth of gauge theory, as I will substantiate in a short while. At any rate, it began with the theoretical discovery of time-reversal invariant topological insulators (Kane and Mele 2005), soon to be followed by the experimental confirmation (König et al. 2007); it was paralleled by topological superconductors and their Majorana fermions; and culminated so far in a general classification of topological states of matter by (Schnyder et al. 2008, Kitaev 2009). By now thousands of papers have been written on the subject. These developments are of course not without precursors, among them Fröhlich in the 90's and in connection with the quantum Hall effect. Incidentally, the major experimental discovery in particle physics

which occurred during the last decade, and I mean that of the Higgs boson, is likewise rooted in gauge theory.

This is not the place to review the history of gauge theory in any detail, see ¹. It may suffice to say that the power of gauge invariance was first recognized by the mathematician Weyl in 1918. He also coined the name *Eichinvarianz* but missed the correct physical context till 1929. The related notion of vector potential was already known to Maxwell, who credited it to Thomson and to Faraday. Non-Abelian gauge field theories proposed by Yang and Mills in 1954 made their way to particle physics. Later the natural setting of gauge symmetry was found to be that of fibre bundles and connections. These notions may be illustrated by an easily visualized example.

Consider the tangent bundle of a sphere (see Fig. 1), i.e. the space of all its tangent vectors, no matter the point at which they are based. That bundle is equipped with a *connection*, which is just a prescription of transporting a vector based at one point of the sphere to another point along a given path. Concretely, we transport that vector parallel to itself in terms of the Euclidean geometry of the ambient space, but just to a nearby point, where it is projected to the corresponding tangent space, and so on repeatedly (and infinitesimally) till destination is reached. Reaching it by a different path yields a different result (see Fig. 2), thus revealing that the sphere is curved even to an



Figure 1: The tangent bundle of the sphere

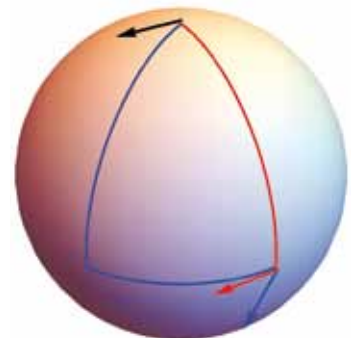


Figure 2: A vector is transported between two points along the red and the blue paths



Figure 3: The sphere fails to be combed, e.g. at the poles



Figure 4: The torus can be combed everywhere

¹ L. O'Raiheartaigh, N. Straumann, Gauge theory: Historical origins and some modern developments. *Rev. Mod. Phys.* 72, 1 (2000)

ant confined to it. The *curvature* integrates to 4π over the sphere and that value does not change upon deforming it. The bundle is moreover *non-trivial*: It is not possible to "comb a hairy ball" or, more precisely, to choose one non-zero vector at each point of the sphere, or at least not in a smooth way (see Fig. 3). This impossibility ties to the $4\pi \neq 0$ just mentioned, as the following example suggests: Replacing the sphere with a torus (a doughnut) the tangent bundle becomes trivial (see Fig. 4) and the curvature integrates to zero.

This picture can be transferred to different contexts almost word by word, proving how versatile these concepts are. In general relativity and in field theory the sphere is replaced by spacetime, but the connection is no longer given beforehand. Moreover, tangent vectors at a point may be replaced by other kinds of vectors representing the values a field can take there. When they are moved from point to point, gauge fields appear by way of the connection. In solid state physics the torus may be viewed as the Brillouin zone of electrons in a 2-dimensional crystal; each of its points is a possible quasi-momentum and the vectors based there are the corresponding Bloch states of energy below the Fermi

level. Unlike for the tangent bundle of the torus, this bundle can be non-trivial as found by Thouless in the context of the integer quantum Hall effect; in fact the curvature integrates to the Hall conductance. We can finally make the link to the aforementioned recent developments. The picture gets a new twist if the Bloch bundle is assumed to enjoy a discrete symmetry, like time-reversal or particle-hole, or both. Though the bundle is then trivial, meaning that one can always "comb" it, we may now ask whether one can do so by means of a pattern which is compatible with that symmetry. The answer is sometimes 'no', which reveals a new class of insulators, now known as topological. Their existence, which previously simply "escaped the radar" (Bernevig), was unveiled by somebody asking a simple math question. It triggered the discovery of new 2-dimensional materials and, not less noteworthy, some 3-dimensional materials already present in nature became novel simply because of a new way of looking at them.

In conclusion, even if mathematical concepts should not fully unify physics, they at least contribute to its advancement by unifying its language.

Annual Meeting in Lugano, 23 - 25 August 2016

The next annual meeting leads us after a long time again to Ticino. It will take place from 23 - 25 August 2016 at the *Università della Svizzera italiana* (USI) in Lugano. The *Swiss Institute of Particle Physics* (CHIPP) will participate again, thus ensuring an interesting program.



We don't want to miss the opportunity to thank Piero Martinoli, USI Director and Albino Zraggen, USI General Secretary for the warm and friendly welcome and their team for the support with the organisation.

- **Tilman Sauer**, Johannes Gutenberg Universität Mainz:
Biography of an Idea: the Case of Gravitational Lensing

Furthermore a public lecture is scheduled on Tuesday evening:

- **Hervé le Treut**, Université Pierre et Marie Curie & Ecole Polytechnique, Institut Pierre Simon Laplace, Paris:
Après la conférence de Paris sur le climat (COP21): quels enjeux et quelle place pour la science?

Scientific Program

Plenary Session

Seven plenary talks will be addressing latest advancements in different research fields:

- **Laura Baudis**, Uni Zürich:
The state-of-the-art in the direct search for dark matter
- **Sibylle Günter**, MPI für Plasmaphysik Garching:
Science with the most modern stellarator, Wendelstein 7-X
- **Laura Heyderman**, PSI Villigen & ETH Zürich:
Artificial Ferromagnetic Systems
- **Jonathan Home**, ETH Zürich:
Trapped-ion quantum state engineering
- **Michele Parrinello**, ETH Zürich & USI Lugano:
Variationally-Enhanced Sampling
- **Aleksandra Radenovic**, EPF Lausanne:
2D-material nanopores as a new playground for biophysics

Topical Sessions

The following parallel sessions will be held in the afternoons:

- Applied Physics and Plasma Physics
- Atomic Physics and Quantum Photonics
- Biophysics and Medical Physics
- Beyond Research – How Physics impacts the Marketplace
- Condensed Matter Physics
- Earth, Atmosphere and Environmental Physics
- Electronic Properties at Surfaces and Interfaces
- History of Physics
- Magnetism and Spintronics at the Nanoscale
- Mott Physics Beyond the Heisenberg Model
- Nuclear, Particle- & Astrophysics
- Theoretical Physics

Dependent on the number and contents of the contributed papers, each topical session will be split into special thematic sub-sessions.

Poster Session

The poster session will be scheduled on 2 days, starting in the evening of 23 August, in the frame of an apéro, and being continued with a lunch buffet on 24 August. It is expected that all posters are put up and being presented on both session days.

The three most outstanding posters will be awarded with a "Best Poster Prize", sponsored by the EPL journal. Additionally to the above requirement, the first author of the poster must be personally present at the conference in order to qualify for the selection.

The maximum poster size is A0 (portrait).

Vendors Exhibition

A vendors exhibition will be organized in parallel to the sessions. An invitation letter will be mailed within the next weeks to interested companies. If your company would like to join the exhibition, but did not receive the letter, please contact: sps@unibas.ch

Award Ceremony

As every year outstanding scientific works will be honoured with the SPS awards, in the respective fields of General Physics (sponsored by ABB Research Center), Condensed Matter Physics (sponsored by IBM Zürich Research Laboratory), Applied Physics (sponsored by OC Oerlikon), Metrology (sponsored by METAS) and new in Computational Physics (sponsored by COMSOL). Each award is granted with CHF 5000.-.

The award ceremony will be held on 23 August in the afternoon.

General Assembly

The general assembly is scheduled for 23 August 2016. The agenda will be published in the next issue of the SPS Communications. We encourage all members to actively participate and contact the committee if special points of interest should be discussed at the assembly.

Excursion

In the morning of the 23 August we will organise a visit to the CSCS (see box). You can register for this visit using the regular registration process on our website.

Important: Since the number of participants is limited, the rule "first come first serve" will be applied.

Conference Dinner

A conference dinner is scheduled for the evening of 24 August. Information on the location, price and more details will be available on our web site soon.

CSCS – Driving innovation in computational research in Switzerland

The Swiss National Supercomputing Centre (CSCS) is opening its doors to those interested in discovering the world of high performance computing. Founded in 1991, CSCS develops and provides the key supercomputing capabilities required to solve important problems in science and/or society. The centre enables world-class research with a scientific user lab that is available to local and international researchers through a transparent, peer-reviewed allocation process. CSCS's resources are open to academia, and are available as well to users from industry and the business sector. During the visit you will learn more about the centre and see the supercomputers that allow researchers to demonstrate science that was never possible with theory and experimentation alone.

Abstract Submission:

Deadline 30 April 2016

You can submit abstracts to all topical sessions. The choice between an oral or a poster presentation of your contribution is possible. Due to the limited number of time slots the session organizers might however be forced to change oral presentations into posters. If possible, please mark both options in your submission, indicating that you are flexible regarding the presentation mode. Abstracts shall not be longer than ca. 100 words, pictures are not allowed.

The submission of abstracts must be done online. Visit our webpage www.sps.ch and follow the link to the submission form. Further explanations are available there. The web-interface will be activated around mid-March.

The full conference program will be available in July 2016 on www.sps.ch. Please check the web regularly for further information and updates.

Conference Fees, Registration and Payment

The conference fees cover the participation to all sessions, including coffee breaks (all days), poster-apéro (Tuesday) and lunch buffet (Wednesday).

The conference dinner on Wednesday evening will be charged separately.

Pay your conference fee in time and save money !

The regular fees, as shown in the table below, hold for payments reaching us before 1 August, 2016.

<i>Category:</i>	<i>CHF</i>
Members of SPS, CHIPP	100.-
Ph.D. Students who are members (*)	80.-
Ph.D. Students who are not members (*)	100.-
Students before Master/Diploma degree (*)	55.-

Plenary speakers, invited speakers, awardees	0.-
Other persons	140.-
Conference Dinner	TBC

(*) Students licence required

For payments done later than 1 August a surcharge of CHF 20.- will be added. This applies also for participants paying cash at the conference.

Attention: Fees are not refundable in case of cancellation. Payment information is available directly during the registration process. Please make sure that your name and the purpose of the payment are indicated.

**Registration Deadline:
1 August 2016**

Special offer for non-members:

Do you plan to participate in our meeting and want to become a member of SPS ? Then take advantage of our special offer of CHF 150.- covering the conference fees and the membership for 2016. (CHF 170.- after 1 August) !

Just fill out the online-registration form, choose the option "Special offer", then download, print, fill and sign the admission form for new members, and return it as soon as possible to the SPS Secretariat.

The membership admission form is available on www.sps.ch/fileadmin/doc/Formulare/anmeldeformular_d-f-e.pdf.

(This offer does not apply for students and Ph.D. students. They still profit from the free first-year-membership and have only to pay the conference fee shown above.)

Additional information for selected sessions

Beyond Research – How Physics impacts the Marketplace

The section "Physics in Industry" proudly announces a dedicated session on "How physics impacts the marketplace" at this year's annual meeting. Invited speakers from corporate research institutions, technology start-ups and academia will provide insights based on their experience on how to successfully bridge the gap between research and the marketplace. It is planned to start the session with a historical overview on the past century and the relevance of physics from pure academic research to new tools and methods in every day life, followed by a discussion of the innovation potential of corporate research organizations versus agile start-ups, which directly leads over to the crucial decision whether to it is preferred to publish or pursue a trade secret strategy. Moreover, best-practice examples will be provided by the founder of a technology-heavy start-up, to illustrate ways on how to overcome barriers to become an entrepreneur. Last but not least, we would like to wrap up the session with a speech about physics in the entertainment sector and how to trigger emotions by "approximate" physics. We are also soliciting contributions for this session and hence encourage you to consider to share your experience on the above topics.

Contact: Thomas Brunswiler (tbr@zurich.ibm.com) and Patrick Ruch (ruc@zurich.ibm.com)

Condensed Matter (KOND)

The condensed matter section of the SPS encourages submission of abstracts to all related focussed sessions (see below). Further topics e.g. magnetism, superconductivity, semiconductors, spintronics, among others will be covered by the regular KOND program.

Contact: Christian Rüegg (christian.rueegg@psi.ch)

Electronic Properties at Surfaces and Interfaces

The session on "Electronic properties at surfaces and interfaces" will be dedicated to the newest developments and investigations of novel electronic states confined at surfaces or interfaces employing large facility based spectroscopies and other techniques. The material systems that will be covered range from thin films over oxide heterostructures to topological insulators.

Contact: Ming Shi (ming.shi@psi.ch) and Thorsten Schmitt (thorsten.schmitt@psi.ch)

Magnetism and Spintronics at the Nanoscale

This session brings together scientists investigating magnetic phenomena or spin transport in systems with restricted dimensions. The major focus is given to experimental and theoretical aspects of static and dynamic spin manipulation, as well as recent advances on spin transport and spin injection effects, in thin films, interfaces and nanostructures. Invited presentations will be given by Dirk Grundler (TU Munich, Functional Thin Films) and Pietro Gambardella (ETH Zurich, Magnetism and Interface Physics).

Contact: Naëmi Leo (Naemi.Leo@psi.ch), Anna Suszka (anna.suszka@psi.ch), Laura J. Heyderman (laura.heyderman@psi.ch)

Mott Physics Beyond the Heisenberg Model

The SNF Sinergia Network organises an international workshop and topical session on the physics of systems with strong spin-orbit coupling. This follows a series of international workshops on the same topic at EPFL (2012), on Monte Verita (2013), and in Oxford (2014). The organisers invite submissions of abstracts by anybody interested in the topic.

Contact: Henrik Rønnow (henrik.ronnow@epfl.ch)

News from SPS Committee meetings (Autumn 2015)

A few years ago, the European Physical Society introduced an initiative to recognize places with international significance to the history of physics in Europe as EPS Historic Sites. The house at the Kramgasse 49 in Bern, where Einstein lived during his *annus mirabilis*, is today a museum. In a joint action of EPS and APS, and in presence of SPS committee members, a commemorative plaque was deposited on Einstein's house, Kramgasse 49 in Bern on 14th September 2015 (see *SPG Mitteilungen Nr. 47*, p. 46). This will further stimulate visits to Einstein's apartment, a place to visit to better situate, within every day life environment, this cradle of a fundamental change of perception of the world.

Discussions to strengthen the links between VSMP and SPS have progressed to encourage membership to both societies at reduced prices. Please read the articles below for details about this agreement. It will help further consolidating common actions for promoting teaching at the gymnasial level.

Following the letter to FC Mrs Doris Leuthard, some of us have had a first meeting on energy issues with Rolf Schmitz (Office fédéral de l'Energie (OFEN) / Bundesamt für Energie (BFE)) and the president of CORE (Commission fédé-

rale de la recherche énergétique / Eidgenössisches Energieforschungskommission), Tony Kaiser, on 2nd December at EPFL, to try to define themes on which the SPS could focalize.

During this period of autumn 2015, members of the Committee have also participated to the following meeting and events: VSMP meeting in Bellwald, 5 - 6 Sept., EPS Energy group (Rome, 23 - 24 Sept.), platform MAP meeting (Bern, 23 Sept.), CRP course for teachers (22 - 24 Sept. in Champéry), YPF event in Bern (2 - 3 Oct., see p. 38), Symposium on general relativity at ETHZ (12 - 14 Nov., see p. 39), Séminaire Dautreppe in Grenoble (4 - 7 Dec., see p. 41), IYL2015 closing ceremony at EPFL (5 Dec., see p. 44).

A member of the Swiss Physics Olympiad participates again in the Jury of the French Physics Olympiads in Jan. 2017.

The 2017 annual meeting, again together with the ÖPG, will be held in Switzerland. The location and period of this joint meeting is under consideration by the Committee.

Antoine Pochelon, SPS Secretary



SPG und VSMP verstärken ihre Zusammenarbeit - Attraktive Doppelmitgliedschaft



Die Schweizerische Physikalische Gesellschaft (SPG) und der Verein Schweizerischer Mathematik- und Physiklehrkräfte (VSMP) werden in Zukunft enger zusammenarbeiten. Die beiden Vorstände haben eine Vereinbarung unterzeichnet, welche zum beiderseitigen Nutzen unter anderem die gemeinsame Organisation von Anlässen (z.B. Vortragsabende, Workshops etc.), in Zusammenarbeit mit der Deutschschweizerischen Physikkommission (DPK) und der Commission Romande de Physique (CRP)¹, beinhaltet.

Kernstück der Vereinbarung ist die neue Doppelmitgliedschaft, welche den Mitgliedern beider Gesellschaften ab 2016 angeboten wird. Die Mitgliedsbeiträge für Doppelmitglieder sind gegenüber den jeweiligen Einzelbeiträgen wie folgt vergünstigt:

Ordentliche Mitglieder zahlen in der SPG nur CHF 60.- statt CHF 80.-. Im VSMP beträgt der Mitgliedsbeitrag nur CHF 30.- statt CHF 40.-.

Wichtig: Dieses Angebot gilt nur für ordentliche Mitglieder, die bisher den vollen Mitgliedsbeitrag zahlen. Beitragsrabatte können nicht kumuliert werden, d.h. profitiert ein Mitglied bereits von einer Beitragsreduzierung aufgrund einer Doppelmitgliedschaftvereinbarung mit einer anderen Partnergesellschaft oder von sonstigen Vergünstigungen, kann kein weiterer Rabatt aufgrund dieser Vereinbarung gewährt werden.

Bestehende Mitglieder einer oder beider Gesellschaften, welche in den Genuß dieser Vergünstigung kommen wollen, gehen wie folgt vor:

Sie sind bereits Mitglied bei SPG und VSMP:

Melden Sie sich bitte formlos beim SPG Sekretariat (sps@unibas.ch). Nach dem Abgleich erhalten Sie von der SPG eine korrigierte Beitragsrechnung, beim VSMP wird die Reduktion ab der nächsten Beitragsperiode berücksichtigt.

¹ Die zwei ständigen Kommissionen des VSMP, zuständig für die Physik und den Physikunterricht.

Sie sind SPG Mitglied, aber noch nicht Mitglied im VSMP:

Melden Sie sich unter www.vsmg.ch/mitglied.php an und geben Sie im Feld "Bemerkungen" Ihre SPG Mitgliedsnummer an (zu finden auf Ihrer aktuellen Beitragsrechnung). Der VSMP meldet der SPG Ihren Eintritt und Sie erhalten anschließend eine korrigierte Beitragsrechnung.

Sie sind VSMP Mitglied, aber noch nicht Mitglied der SPG:

Verwenden Sie das Anmeldeformular, welches unter www.sps.ch/fileadmin/doc/Formulare/anmeldeformular_d-f-e.pdf heruntergeladen werden kann, und senden es an das SPG-

Sekretariat. Die SPG meldet dem VSMP Ihren Eintritt und die Reduktion wird ab der nächsten Beitragsperiode berücksichtigt.

Die Vorstände von SPG und VSMP sind überzeugt, mit dieser Zusammenarbeit und der attraktiven Doppelmitgliedschaft die Physikgemeinde in der Schweiz noch besser zu vernetzen, Synergien zu nutzen und noch besser auf die aktuellen Fragen und Probleme der Physik eingehen zu können. Insbesondere hoffen die beiden Vorstände, daß diese Zusammenarbeit dazu beiträgt, die Attraktivität der Physik sowohl für Mittel- als auch Gymnasialschüler zu steigern.



La SSP et la SSPMP renforcent leur coopération – offre attractive pour une affiliation simultanée aux deux sociétés



La Société Suisse Physique (SSP) et la Société Suisse des Professeurs de Mathématiques et de Physique (SSPMP, VSMP) collaboreront plus étroitement l'avenir. Les deux comités ont signé un accord pour le bénéfice mutuel des deux parties qui comprend l'organisation d'événements conjoints (par exemple conférences en soirée, ateliers, etc.), en coopération avec la Deutschschweizerische Physikkommission (DPK) et la Commission Romande de Physique (CRP) ¹.

Le noyau de l'accord est la nouvelle double appartenance offerte aux membres des deux sociétés dès 2016. Les frais d'adhésion pour la double affiliation sont réduits par rapport aux contributions individuelles respectives comme suit:

Les membres ordinaires ne paient que CHF 60.- à la SSP au lieu des CHF 80.-. Dans le cas de la SSPMP, la cotisation ne s'élève plus qu'à CHF 30.- au lieu des CHF 40.-.

Important: Cette offre n'est réservée qu'aux membres réguliers qui paient jusqu'à maintenant l'entier des frais d'adhésion. Les réductions de contributions ne peuvent être combinées, c'est-à-dire que si un membre bénéficie déjà d'une réduction de prime due à une convention de double appartenance avec une autre société partenaire ou d'autres avantages, aucune réduction supplémentaire ne peut être accordée d'après cet accord.

Les membres de l'une ou de l'autre des deux sociétés qui veulent bénéficier de cet avantage procéderont comme suit:

¹ Les deux commissions permanentes de la SSPMP, responsables de la physique et de l'enseignement de la physique.

Vous êtes déjà membre de la SSP et de la SSPMP:

Veuillez vous adresser de manière informelle au Secrétariat de la SSP (sps@unibas.ch). Après vérification vous recevrez une facture corrigée de la contribution à la SSP, pour ce qui concerne la SSPMP, la réduction de la cotisation sera prise en compte sur la période suivante.

Vous êtes membres de la SSP, mais pas encore de la SSPMP:

Veuillez vous inscrire au site www.vsmg.ch/mitglied.php et entrer dans le champ "Remarques" votre numéro de membre SSP (qui se trouve sur votre actuelle facture de cotisation). La SSPMP avisera la SSP de votre inscription et vous recevrez par la suite une facture de contribution corrigée.

Vous êtes membre de la SSPMP, mais pas encore membre de la SSP:

Utilisez le formulaire d'inscription, qui peut être téléchargé depuis http://www.sps.ch/fileadmin/doc/Formulare/anmeldeformular_d-f-e.pdf, et envoyez le au Secrétariat de la SSP. La SSP annonce votre inscription à la SSPMP et la réduction entre en vigueur à la prochaine période de contribution.

Les comités de la SSP et de la SSPMP sont convaincus qu'avec cette coopération et ce statut de double membre attractif on parviendra encore mieux à réseauter la communauté des physiciens en Suisse, de mieux exploiter les synergies et de mieux répondre aux questions et aux problèmes actuels de la physique. En particulier, les deux comités espèrent que cette coopération contribuera à renforcer l'attractivité de la physique à la fois pour les élèves des écoles secondaires et du niveau gymnasial.

Hommage à Francis Troyon, Membre d'honneur de la SSP

En juin 1962, un jeune physicien théoricien de l'université de Rochester, le Docteur Francis Troyon, se joignait à une petite équipe du Laboratoire de Physique des Plasmas, fondé à Lausanne le 1er mai 1961. Lors de la manifestation scientifique à l'occasion de sa leçon d'honneur, fin mars 1999, des personnalités scientifiques internationales de premier plan vinrent à l'Ecole Polytechnique Fédérale de Lausanne (EPFL) rendre hommage au Professeur Francis Troyon, Directeur du Centre de Recherches en Physique des Plasmas (CRPP), un des fers de lance de la recherche européenne et mondiale en énergie de fusion et en physique des plasmas. En un peu moins de quarante années, les qualités scientifiques et politiques du Professeur Troyon ont ainsi réussi à placer l'Ecole Polytechnique Fédérale de Lausanne (qui a repris le CRPP en 1973) et la Suisse comme un des grands acteurs de la fusion, et ceci malgré la taille de notre pays.



Francis Troyon était ingénieur-physicien de l'Ecole Polytechnique de l'Université de Lausanne, l'EPUL qui devint l'EPFL en 1969, puis partit à l'Université de Rochester faire une thèse de doctorat. A son retour en Suisse, il mit en application ce qu'il recommandait aux jeunes dans son allocution de départ (à savoir d'oser changer de métier) et se lança dans cette nouvelle discipline qu'était alors la physique des plasmas de fusion. Il fut nommé Professeur Titulaire en 1974, devint Directeur du CRPP en décembre 1981 et Professeur Ordinaire en 1983.

Le thème central de sa recherche était l'étude par la simulation numérique de la stabilité du plasma confiné par des champs magnétiques (comme celle de la configuration dite du tokamak) et, plus généralement, la simulation des phénomènes physiques dans les plasmas confinés magnétiquement. Mais, Francis Troyon appartenait à cette génération de scientifiques, qui non seulement étaient des experts dans leur domaine, mais avaient une vision et des connaissances extrêmement larges sur toute la physique des plasmas. Il imprimait pour le CRPP dans les années 80 des orientations, qui, vingt à trente ans plus tard, ont permis à notre laboratoire d'être une des unités de recherche européennes et mondiales les mieux cotées. Citons par exemple la simulation par ordinateurs, l'étude de l'influence des formes du plasma de tokamak dans le Tokamak à Configuration Variable TCV du CRPP, leur chauffage par ondes électromagnétiques à très haute fréquence. C'était sous son impulsion que les recherches en plasmas industriels ont débuté. C'est encore sous sa Direction, que les activités en technologie de fusion effectuées à l'Institut Paul Scherrer ont été intégrées au CRPP.

Francis Troyon a été un de ceux qui avaient la vision que notre recherche en énergie de fusion devait s'intégrer à celle de l'Union Européenne. Il a activement participé à la négociation de l'Accord de Coopération entre la Suisse et l'Euratom de 1978, le premier accord bilatéral de la Suisse

avec la Communauté Européenne! Il faut souligner ici tous les aspects positifs de cette association, comme la pleine intégration au Programme Euratom Fusion, la participation au projet européen JET ou mondial ITER, avec d'importantes retombées scientifiques, industrielles et aussi la possibilité d'avoir une formation de pointe. Les qualités humaines et politiques de Francis Troyon l'ont amené aux plus hautes responsabilités au niveau européen comme la Présidence du Conseil Scientifique de JET, celle du Conseil de JET. Il fut également membre du conseil scientifique international qui a défini le projet ITER.

A côté de ses activités scientifiques et internationales, Francis Troyon a aussi été un enseignant hors pair. Il a su passer son enthousiasme non seulement pour la physique des plasmas, mais tout simplement pour la physique en général et les mathématiques aux étudiants qui ont eu la chance de l'avoir comme enseignant ou comme directeur de thèse. A côté de son enseignement, un de ses messages a aussi été l'importance de l'éthique, le socle sur lequel tout doit être construit. Ce qui est frappant pour les nombreuses personnes qui l'ont côtoyé dans l'exercice de son enseignement ou de sa direction, c'est le temps qu'il a toujours su accorder à la discussion, à la recherche de solutions. Il y a chez lui à la fois cette attitude sincère de recherche et l'attitude du maître – on a presque envie de dire du père – pour ses collaborateurs plus jeunes qu'il a formés à travers ces dialogues, et dont le contenu portait le plus souvent sur la mise en évidence des enjeux scientifiques dignes d'être poursuivis sur le long terme.



Francis Troyon entouré d'une partie de sa famille lors de la cérémonie à l'occasion de laquelle l'EPFL lui a accordé le titre de Professeur Emérite.

La Société Suisse de Physique en reconnaissance de ses contributions pour la physique des plasmas l'a nommé membre d'honneur en 2014. La citation mentionne : « Le titre de membre honoraire de la Société Suisse de Physique est attribué à Francis Troyon pour ses contributions majeures pour le développement de la physique des plasmas et de la fusion en Suisse et dans le monde ».

Francis Troyon (1933-2016) nous a quitté le 10 janvier 2016. Il était un homme de conviction, un scientifique d'exception et un enseignant hors du commun. Cette perte attriste beaucoup d'entre nous, ses anciens collègues, collaborateurs ou étudiants. La SSP se joint à ses nombreux amis de par le monde pour exprimer ses sincères condoléances à sa famille.

Antoine Pochelon & Minh Quang Tran

Progress in Physics (52)

Seeing quantum superpositions

Nicolas Sangouard, Department of Physics, University of Basel

Introduction

In quantum theory, a single particle — a photon for example — can occupy two spatial positions simultaneously. Surprisingly, this superposition principle is supposed to hold at any scale as quantum theory makes no distinction between small and large systems. To better account for what we observe in our daily experiences where classical behaviors readily emerge, theorists and experimentalists have been working hand in hand for decades to probe the limits of the superposition principle.

Nowadays, decoherence is widely accepted as one of the fundamental problems limiting the ability of macroscopic systems to maintain quantum features. As the size of a quantum system increases, it increasingly interacts with its surroundings, rapidly losing its quantum properties. Several experiments, such as the use of Rydberg atoms for probing the electromagnetic field of a high-finesse cavity [M. Brune et al. PRL 77, 4887 (1996)] or the use of a trapped ion interacting with engineered reservoirs [C. Monroe et al. Science 272, 1131 (1996)], are beautiful illustrations of this idea.

However, even if a macroscopic system is sufficiently decoupled from the environment, its quantum features remain difficult to observe. In particular, the observation of its quantum nature requires extremely precise measurements [see e.g. N. Mermin, Phys. Rev. D 22, 356 (1980) or more recently P. Sekatski et al. Phys. Rev. Lett. 113, 090403 (2014)]. This naturally raises the question of whether the human eye — with its many imperfections — can see quantum superpositions. It might be that quantum theory applies at any scale but the eye cannot reveal it, i.e. provides an erroneous classical description of the physical reality that is quantum even at macroscopic scales.

Method description

The response of the human eye to light pulses with various intensities has already been studied [F. Rieke and D. A. Baylor, Rev. Mod. Phys. 70, 1027 (1998)]. In particular, in the few photon regime, experimental results indicate that at a wavelength of 500 nm, human vision can be modeled by a threshold detector preceded by loss, i.e. a detector with a threshold at 7 photons with an efficiency of 8%. This means that about two hundred photons in average need to be sent into the eye to get a high enough excitation in the brain to consciously see light.

One may then wonder whether there is a practical way to create quantum superposition states with a sufficiently large photon number so that its quantum nature can be detected with the eye. The task is a priori challenging. Since current technologies can only produce superpositions with small photon numbers, one may use many independent quantum superpositions, each made with a few photon numbers.

Although certain collective measurements of these independent superpositions can reveal their quantum nature [N. Brunner et al. Phys. Rev. A 78, 052110 (2008)], the realistic model of the eye that is described before cannot. Another example is the proposal presented in [P. Sekatski et al. Phys. Rev. Lett. 103, 113601 (2009)] where single photons are amplified through a cloning operation. It has been shown that the resulting superpositions could be revealed with human-eye based detectors in this scenario only if very strong assumptions are made on the source. For example, it is necessary to assume that the source produces true single photons which can be entirely described in a basis made with two states only [E. Pomarico et al. New J. Phys. 13, 063031 (2011)].

Together with Valentina Caprara Vivoli, a PhD student in the Group of Applied Physics at Geneva, and Dr. Pavel Sekatski, a senior postdoc in the Institute for Theoretical Physics in Innsbruck, we go beyond state of the art methods by making a concrete yet simple proposal for experimentally testing the capability of the human eye to see quantum superpositions. The principle of our proposal is shown in Fig. 1.

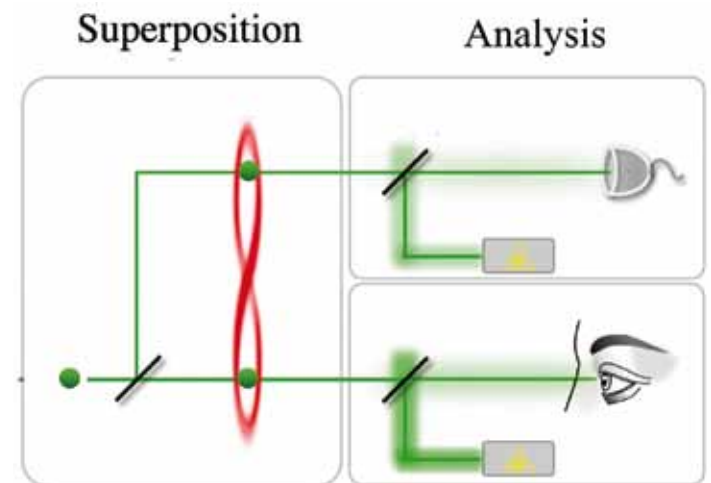


Fig. 1. Principle of the proposal to test the capability of the human eye to observe quantum superpositions. The superposition is created by sending a single photon into a balanced 50/50 beamsplitter. The reflected mode is analyzed by a standard photon detector while an eye based detection is used for the transmitted mode. Both detections are preceded by an unbalanced beamsplitter that is used to combine the mode that is analyzed with laser light. Using laser lights with appropriate intensities and with various phases, we can prove that the photon is in a quantum superposition of being transmitted and reflected by the first beamsplitter.

It starts with a single photon that is sent into a beamsplitter — a kind of partially reflecting mirror which transmits only half of the light. Due to its quantum nature, the photon occupies both the transmitted and reflected modes after the beamsplitter, i.e. it is in a quantum superposition of two different spatial modes. Physicists write that the state after the beamsplitter is

$$|\psi_{-}\rangle = \frac{1}{\sqrt{2}}(|1\rangle_t|0\rangle_r - |0\rangle_t|1\rangle_r)$$

where $|1\rangle_t$ means one photon in the transmitted mode for example. To verify this, the transmitted part is sent into an eye whereas the reflected mode is analyzed by a standard photon detector. The latter clicks if at least one photon occupies the reflected mode, i.e. is a detector with a threshold at 1 photon. Without additional elements, the single photon detector would click half of the experimental runs while the eye would never see light. This cannot prove that the photon is a quantum superposition, since a completely classical scenario in which a single photon is produced half of the runs and systematically sent into the photon detector would lead to the same detection events.

The trick for proving that the single photon is in a quantum superposition state is to combine both the reflected and transmitted modes with laser light into unbalanced beamsplitters, see Fig. 1. Thank to an interference at the beamsplitter, the superpositions with opposite phases

$$\frac{1}{\sqrt{2}}(|1\rangle + |0\rangle) \text{ and } \frac{1}{\sqrt{2}}(|1\rangle - |0\rangle)$$

become distinguishable, i.e. they lead to two different probability distributions in photon number. As an example, we see in Fig. 2 that for a laser intensity such that 100 photons of the laser light are reflected in average, the probability distributions can be well distinguished with a threshold detector that would only click if the photon number is larger than 100. This means that we can distinguish the superposition states

$$\frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$$

with any threshold detector by controlling the laser intensity to adapt the number of reflected photons to the threshold of the detector.

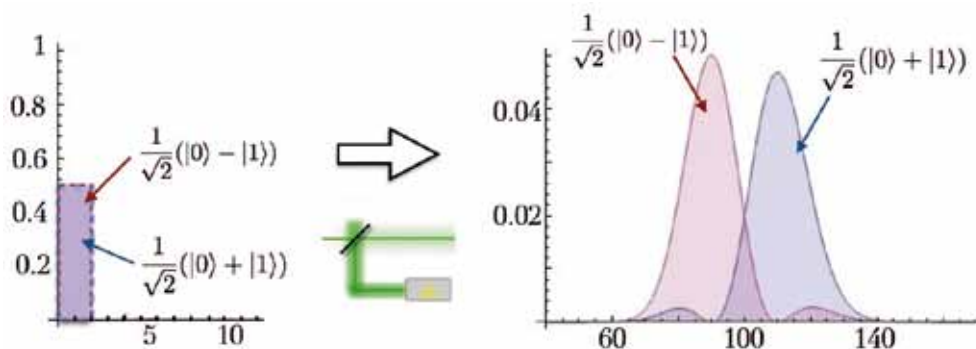


Fig. 2. The figure on the left shows the probability of finding n photons when measuring the photon number in the superposition states

$$\frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$$

In both cases, we can find 0 photon and 1 photon only, with equal probabilities. The figure on the right shows the probability of finding n photons when the previous superposition states are combined into a beamsplitter along with laser light so that 100 laser photons in average are reflected. The two probability distributions are now distinguishable: When their photon number is measured, one of them more often shows photons numbers smaller than 100 while the other one mostly indicates photon numbers larger than 100. This is due to an interference effect at the beamsplitter in which most of the laser photons are reflected or transmitted depending on the phase of the superposition states.

What we have proposed is to adjust the intensity of the upper laser in Fig. 1 so that 1 photon in average is added to the mode reflected by the first beamsplitter. When the photon detector clicks, this essentially projects the state of the transmitted mode into

$$\frac{1}{\sqrt{2}}(|0\rangle_t - |1\rangle_t)$$

i.e. is not seen by the eye even when the corresponding laser is tuned to the right intensity. Similarly, when the detector does not click, the transmitted mode is projected in

$$\frac{1}{\sqrt{2}}(|0\rangle_t + |1\rangle_t)$$

which can be seen by the eye upgraded by appropriate laser intensity. By changing the phase of both lasers, we can prove that the photon after the first beamsplitter is coherently delocalized between the reflected and transmitted modes, i.e. the photon is in a quantum superposition. Crucially, this can be shown without assumption on the photon number in each mode nor on the way the state has been created.

Outlook

A detailed feasibility study in which the photon is created by a currently available source and taking into account the loss along the way from the source to the detectors as well as the detector/eye efficiencies, has confirmed that quantum superpositions can be revealed in the setup of Fig. 1 with present day technologies. Such an experiment would be the first one where the human eye is used to reveal the quantum nature of photonic states. From a practical point of view, such an experiment would show that a very coarse grained detector — here the eye — can be upgraded by laser light up to the point where it becomes useful for quantum experiments. It would be interesting to show that this simple technique can be applied to any detector, including noisy detectors, such as the widely available cameras in our smartphones. Anyway it is safe to say that probing human vision with quantum light is a *terra incognita*. This makes it an attractive challenge on its own.

Acknowledgments

I thank Melvyn Ho for a careful reading of the manuscript. This work could not have been realized without the financial support of the John Templeton Foundation, the Swiss National Science Foundation (SNSF) through the NCCR QSIT and Grant number PP00P2-150579. The open mindedness of these foundations make them unique.

Progress in Physics (53)

The physics of data centers – beyond the transistor node

Patrick Ruch, Thomas Brunschwiler, IBM Research – Zurich

Introduction

In 1974, Robert Dennard et al. described the physics of how to shrink a field-effect transistor (FET) while maintaining its performance characteristics (Dennard et al., 1974). The beauty of the so-called Dennard scaling was that the power consumption of a FET per unit area was constant, so that populating the same microprocessor area with more FETs of smaller dimensions would make the system faster, but not more power-hungry. This conclusion was certainly valid for the FETs developed in the early 1970s; however, substantial advances in the photolithographic techniques, gate materials and transistor geometries used by the semiconductor industry have reduced the gate length to less than 20 nm and the equivalent gate oxide thickness to about 1 nm. This evolution toward atomically thin gate oxides has resulted in increased gate leakage currents, whereas the reduction in supply voltage to ~ 1 V has resulted in a substantial increase in the subthreshold leakage currents (Roy et al., 2003). These leakage currents are responsible for a considerable amount of power consumption even when the chip is idle (Nowak, 2002). The combination of these physical limits at the nanometer scale and limited power delivery and heat dissipation at the centimeter scale has stalled traditional transistor scaling and resulted in a saturation of clock speed and chip power (Borkar & Chien, 2011; Shalf et al., 2009).

Outside of the classical FET, there is still significant room for improvement of microprocessor performance and energy efficiency. For example, the metallic interconnects forming the short-range on-chip wiring suffer from increased surface scattering after scaling beyond the 50 nm node (Davis et al., 2001), whereas global interconnects spanning across the chip do not scale well because the chip size has remained roughly constant (Borkar, 2013). The disparity in interconnect scaling and transistor scaling means that the majority of power supplied to a chip is spent on data transmission via interconnects rather than computation via FETs (Moore & Greenfield, 2008). Moreover, the scaling of interconnects for data transmission suffers at the chip edge, where solder interconnects at a fairly large pitch (i.e., more than $100 \mu\text{m}$) bridge to the printed circuit board (PCB). This limits communication bandwidth and results in a competition between

interconnects allocated to the power supply and those used for data transmission (Stanley-Marbell et al., 2011).

These developments have spurred interest in alternative approaches to value creation in the design of computers. They include key enabling technologies, such as 3D packaging (Knickerbocker et al., 2008; Ramm et al., 2010), advanced heat dissipation (Brunschwiler et al., 2008) and power delivery (Andersen et al., 2014; Chang et al., 2010). Further, the thermodynamics of the entire datacenter facility needs to be revisited (Brunschwiler et al., 2009; Shah et al., 2008) to ensure efficient use of energy and counteract the increasing electricity consumption of computing systems worldwide (Koomey, 2011; Van Heddeghem et al., 2014). Our contribution describes a selection of scientific and technological innovations to address the above challenges. Overall, the physics of computing systems spans 12 orders of magnitude in characteristic length scales (Figure 1), thereby representing a formidable range of scientific and technological challenges.

The ideal chip package – power in, heat out, and abundant bandwidth

Wiring congestion has evolved into an important challenge in modern microprocessors. The availability of vertical electrical interconnects, so-called through-silicon vias (TSVs), enables the stacking of integrated circuit (IC) dies to overcome the chip-edge interconnect and wiring limitations (Figure 2a) (Erdmann et al., 2014; Khurshid & Lipasti, 2013). In this way, the bandwidth, latency and energy efficiency for die-to-die communication can be reduced by an order of magnitude thanks to proximity and improved interconnect densities.

However, the interface area for power delivery and heat removal to and from the chip stack stays invariant, whereas the electrical and thermal interfaces scale proportionally to the number of dies in the chip stack. Thus, novel materials and technologies are key to support the scalability of power delivery and heat removal. We will discuss two novel material formulations supporting current 3D chip-stack topologies with power delivery through the front and heat removal through the back-side of a chip stack. Both benefit from

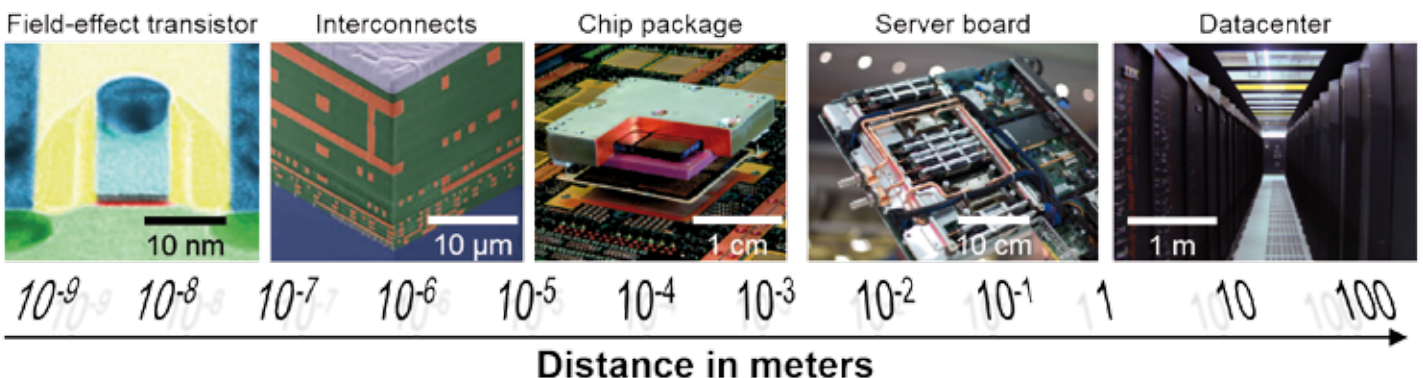


Figure 1: Characteristic length scales of computing systems.

nanoscale effects to improve thermal or electrical transport across interfaces. A topology change towards volumetric heat removal and power delivery through embedded fluid networks, providing access to coolants and electrolytes into the chip stack is also discussed, with the main focus on electrochemical power delivery.

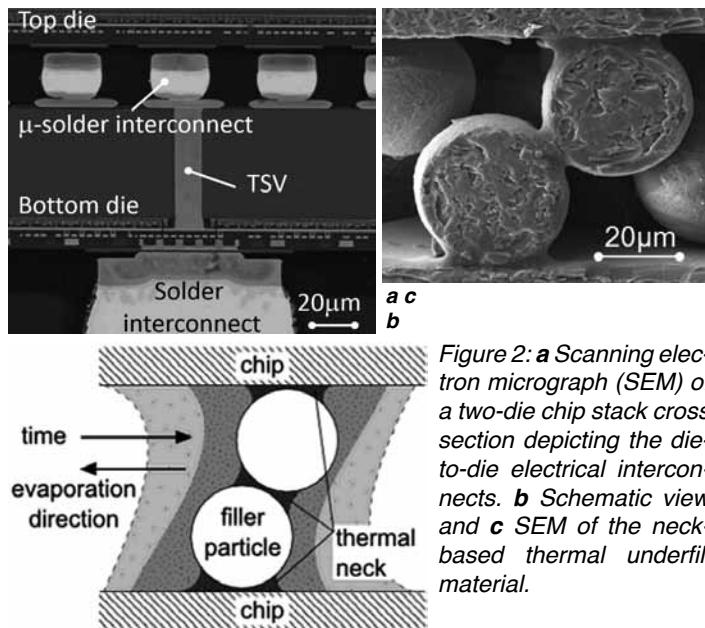


Figure 2: **a** Scanning electron micrograph (SEM) of a two-die chip stack cross section depicting the die-to-die electrical interconnects. **b** Schematic view and **c** SEM of the neck-based thermal underfill material.

To mitigate thermal gradients within the chip stack, a neck-based composite material with enhanced thermal conduction can be infiltrated between the microsolder interconnects, which impose a natural thermal barrier owing to the low area fill fraction of the solder interconnects (Brunschwiler et al., 2012). The infiltration procedure is performed in three main steps: first, micron-sized alumina filler particles are accumulated between the IC dies using centrifugal forces. Second, an aqueous nano-suspension is induced into the percolating particle bed by capillary action. During the subsequent evaporation procedure of the dispersant, capillary bridges, such as in wet sand, form between the filler particles and the concentration of alumina nanoparticles in the suspension increases. As a result, the nanoparticles assemble and form quasi-areal contacts, so-called necks in the point contact regions of the filler particles. Third, the remaining pores are filled with an epoxy, which is cured to provide the required mechanical integrity and chip-stack reliability. Thermal transport between the IC dies could be improved three-fold by means of the neck-based thermal underfill compared with state-of-the-art materials, thus supporting heat dissipation to the heat sink attached to the back-side of the chip stack (Zürcher, et al., 2015).

The ultimate heat-removal approach, which scales with the number of dies in the chip stack, is the introduction of microchannels between the active dies (Figure 3) (Brunschwiler et al., 2008). Coolants such as water can be pumped by a pressure gradient through the microchannels, which have a hydraulic diameter of $\sim 50 \mu\text{m}$, to remove the dissipated heat by convection in close proximity of the transistors. Die-to-die communication can still be maintained by embedded TSVs in the microchannel walls. Sealing rings around TSVs prevent electrical shorting through the liquid. The dissipation of power densities of up to 3.9 kW/cm^3 was demonstrated on lab-scale test vehicles, while maintaining the thermal

budget of 85°C maximal junction temperature (Brunschwiler et al., 2010).

The increased power levels supported by the discussed heat-removal methods require also novel power-delivery concepts and technologies to achieve a balanced system performance. Currently, an array of lead-free solder interconnects is used as interface between the PCB and the bottom-most die in the chip stack. During a reflow process with temperatures above the liquidus temperature of the solder (e.g. 260°C for SnAgCu alloys), the copper pads of the mating components are wetted, resulting in electrical interconnects with a threshold current of up to 200 mA, defined by electromigration (Tong et al., 2013). The high joining temperature in combination with the two disparate thermal-expansion coefficients of the mating components (i.e., 2.3 ppm/K for the silicon die and $\sim 18 \text{ ppm/K}$ for the PCB) result in mechanical shear above the solder yield strength, causing plastic deformation. Moreover, during the joining process, a brittle intermetallic compound is formed at the pad-solder interface. Both effects can cause interconnect failure, compromising the lifetime of the server product (Wang et al., 2012).

To overcome the limitations of solder interconnects, all-copper interconnects formed at low temperatures are being proposed (Zürcher et al., 2015) (Figure 3b). A copper paste consisting of a bi-modal distribution of copper nano- and micro-particles with a diameter 15 nm and $3 \mu\text{m}$, respectively, is formulated in an organic dispersant. To prevent the oxidation of particles after their synthesis, surface functionalization is applied in the reactor in inert gas conditions. By means of doctor-blading, a thin film of the paste with

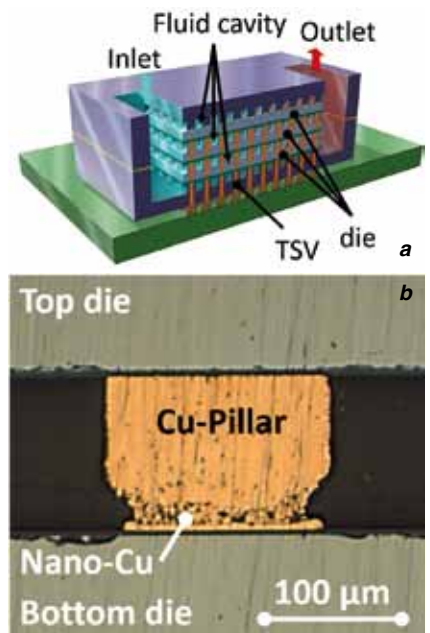


Figure 3: **a** Isometric view of an inter-layer-cooled 3D chip stack with embedded fluid channels.

b Optical micrograph of an all-copper interconnect cross section.

a thickness of $20 \mu\text{m}$ results. On the IC die, an array of copper pillars is formed by electrodeposition as substitution of the solder-ball array. The copper paste is transferred to the tips of the copper pillars of the IC die by means of a dipping process in a flip-chip bonder. Subsequently, the die is aligned and placed on the PCB. The paste now bridges the area between the copper pillar and the pad on the PCB. Then the evaporation of the organic binder, the desorption of the surface functionalization, and the annealing of the copper nano- and micro-particle agglomeration are done in an oven at temperatures as low as 200°C (i.e., below the liquidus temperature of copper, which is 1084°C) in a formic-acid atmosphere to reduce any residual copper oxide. As a result, an all-copper electrical interconnects is formed at substantially lower joining temperatures, without formation

of intermetallic compounds and with better electromigration resistance than solder joints. Moreover, these interconnects support the power-density scaling, while maintaining system reliability.

A fundamental change in the power-delivery architecture in the form of a liquid-cooling/redox-flow hybrid fluid network has been proposed based on the integrated microchannels in the chip stack, which previously only served to dissipate heat from the volume (Ruch et al., 2011). Adding redox-active molecules or ions to an aqueous solution enables convective transport of chemical energy along with the cooling water, equivalent to grid-scale redox flow batteries (Skylas-Kazacos et al., 2011). The conversion of chemical energy into electrical energy via an electrochemical cell embedded in the fluid network allows the multiple voltage conversion stages used in the conventional power-delivery chain in a datacenter (Pratt & Kumar, 2007) to be bypassed. Further, as the heat dissipation and the power demand on a chip are locally congruent, the concept of using one fluid network for both cooling and power delivery appears attractive in terms of energy efficiency.

It is illustrative to compare the energy penalty of charge transport via electrical wires with the convective transport of ions in a liquid conduit. For a current flowing through a wire, the main loss mechanism is Joule heating, whereas for laminar fluid flow through microchannels, it is friction loss. The critical diameter D_{crit} for which the Joule heating in a wire is equivalent to the friction loss in a pipe is derived as

$$D_{crit} = \frac{1}{fzF} \sqrt{32\mu\sigma} \quad (1)$$

where σ is the electrical conductivity of the wire and μ the viscosity of the fluid. For convective transport of a redox species at a volumetric flow rate v_L and a concentration c , an equivalent current $I = czFv_L f$ can be calculated, where z is the number of electrons exchanged in the redox reaction and F is Faraday's constant. The coefficient f represents the fraction of redox molecules converted during the electrochemical discharge ($0 \leq f \leq 1$).

For $\mu = 20$ mPa·s (concentrated electrolyte solution), $\sigma = 6 \cdot 10^7$ S/m (copper), $c = 1$ mol/L and $z = 1$, $D_{crit} = 64/f \mu\text{m}$. For a channel with diameter $D < D_{crit}$, charge transport is more efficient in wires than in fluid channels, whereas for $D > D_{crit}$, convective ion transport in fluids is more efficient. Assuming a conversion rate of 20% of the redox molecules in solution ($f = 0.2$) (Kjeang et al., 2007), charge transport in fluid channels is favorable only in hydraulic diameters

> 320 μm . This magnitude of channel diameter corresponds well to the microchannels used in liquid cooling.

Electrolytic charging of redox electrolytes, on-chip testing of power delivery and heat removal are carried out in an electrochemical fluid loop containing an electrochemical flow cell and a custom-designed thermal test board (Figure 4a). Miniaturized redox flow cells comprising a polymeric semi-permeable membrane or a nanoporous separator together with electrochemically active carbon-fiber electrodes integrated in silicon have been demonstrated (Figure 4b) (Ruch et al., 2015). Preliminary work has shown that an on-chip all-vanadium redox flow battery can be used to power up the caches with an average power consumption of 1 W/cm² (Sabry et al., 2014).

Datacenter thermodynamics– the case for heat recovery, and new perspectives for utilization

The annual electricity consumption in datacenters has been estimated to account for about 30 billion USD or 330 TWh, which represents 2% of the worldwide electricity consumption (Meijer, 2010). The power consumption of 61 standalone datacenters was found to be on average 1.9 times greater than the power consumed by their computing hardware alone (ENERGY STAR, 2014). The overhead is mainly due to the compression chillers, which provide cold air, and to electrical losses in the power-delivery chain. The reason for the high cooling-energy need is the cost-effective but low-performing thermal design of air heat sinks. A measure of the efficacy of a heat sink is its thermal resistance $R_{th} = \Delta T/\dot{q}'$, where ΔT is the mean difference between the chip surface temperature and the cooling fluid and \dot{q}' is the heat flux density. A typical air-cooled heat sink exhibits $R_{th} \approx 0.6$ K cm²/W, and the corresponding temperature difference between chip and coolant for a chip-level power density of 100 W/cm² is 60 K. To maintain chip temperatures below 85°C for reasons of reliability, the temperature of the air entering the heat sink must therefore be cooled to below 25°C.

Besides the direct cost associated with active cooling, there are also thermodynamic implications that affect the overall efficiency of the system. According to the Carnot theorem, the maximum amount of work that can be extracted between the temperature level of the chip surface, T_j , and that of the ambient air, T_a , is

$$\dot{W}_{max} = \eta_c \dot{q}' A = \left(1 - \frac{T_a}{T_j}\right) \dot{Q}, \quad (2)$$

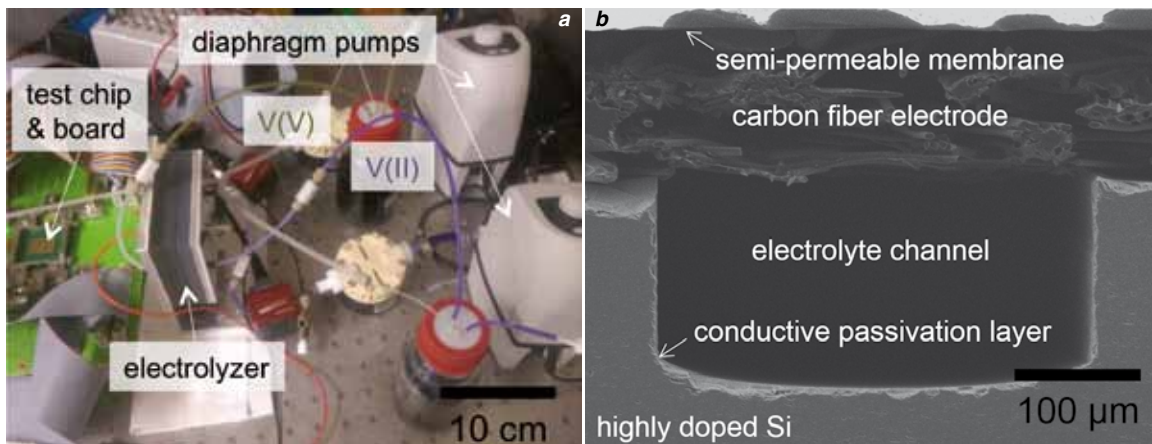


Figure 4: **a** Experimental setup used to generate and test redox electrolytes and cell designs for on-chip electrochemical power delivery. The solutions in the photograph are 1 M V(V) (yellow) and 1 M V(II) (purple), each in 2 M H₂SO₄. **b** SEM of a cross section of an electrochemical half-cell integrated on silicon.

where η_c is the Carnot efficiency, A the chip area and \dot{Q} the total power dissipation. The quantity \dot{W}_{\max} is sometimes referred to as the exergy content of the dissipated heat (Shah et al., 2006). A fundamental difference between exergy and energy is that the former is not conserved. The upper bound to the work that can be extracted from the heat that is actually recovered in the cooling fluid is

$$\dot{W} = \left(1 - \frac{T_a}{T_j - R_{th}\dot{Q}}\right)\dot{Q}, \quad (3)$$

The exergy loss due to thermal resistance is obtained by subtracting Eq (3) from Eq. (2). When $(T_j - R_{th}\dot{Q}) < T_a$, Eq. (3) yields $\dot{W} < 0$, i.e., additional work has to be invested by means of a heat-pump cycle to enable heat rejection to T_a (Brunschwiler et al., 2009).

Based on the above, providing heat sinks with reduced R_{th} has a two potential merits. First, the expression $(T_j - R_{th}\dot{Q})$ can be made greater than T_a to enable heat rejection to ambient without requiring an additional heat-pump cycle, which is referred to as *free cooling*. Second, the exergy content of the recovered heat can be increased, which potentially enables further utilization of the heat rather than discarding it into the environment.

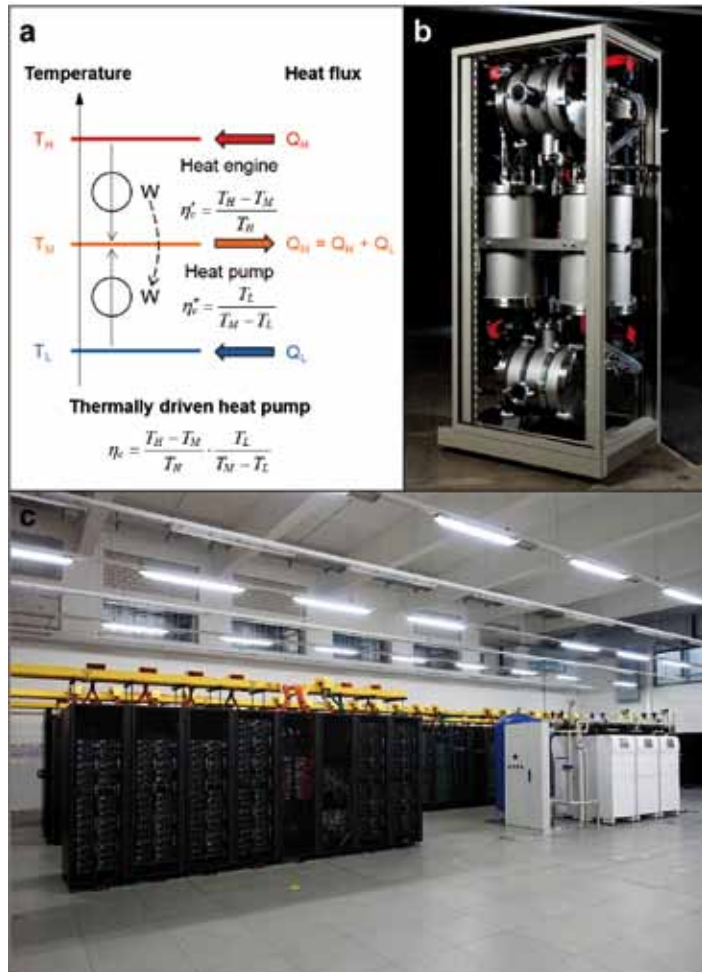


Figure 5: **a** Thermodynamic principle of a thermally-driven heat pump operating with three temperature levels. The Carnot efficiencies of the individual heat transformation stages and the overall Carnot efficiency are given. **b** Experimental adsorption heat pump test rig at IBM Research – Zurich comprising two vertical adsorption chambers, a condenser chamber and an evaporator chamber. The rack height is 2 m. Photograph courtesy of SPF Rapperswil. **c** CoolMUC-2 HPC cluster (left) providing the driving heat for six adsorption chillers (right). Photograph courtesy of SorTech AG.

To this end, direct liquid-cooled heat sinks have been developed with $R_{th} < 0.1$ Kcm²/W (Escher et al., 2010). For fluid outlet temperatures of 60°C, a direct use of the recovered heat in space-heating systems has been demonstrated (Zimmermann et al., 2012). Furthermore, a thermally-driven heat-pump cycle can provide direct conversion of the recovered heat into cooling (Ziegler, 2009). In contrast to a conventional heat-pump cycle based on mechanical compression, there are three characteristic temperature levels for thermally-driven heat pumps: high (T_H), medium (T_M) and low temperature (T_L). The operation can be described thermodynamically as a combination of a heat engine and a heat-pump cycle (Figure 5a).

The heat recovered from datacenters employing servers with low R_{th} can be supplied at temperature T_H to adsorption heat pumps, which rely on the reversible physisorption of a vapor on a solid desiccant (Aristov, 2014). The heat uptake at the low temperature T_L can be used to provide cooling for non-liquid-cooled datacenter components, whereas the T_M level corresponds to the outside ambient, which acts as the final heat sink. High sorption rates and evaporation of liquid water at sub-ambient temperatures are achieved by implementing the desiccant within evacuated sealed vessels (Figure 5b).

Recently, the largest combination of a computing cluster with adsorption chillers to date was put into operation at Leibniz Rechenzentrum (LRZ). An HPC cluster is direct water-cooled, and the recovered heat is supplied at up to 60°C to six adsorption chillers with a nominal cooling power of up to 16 kW each (Figure 5c). The chilled water is supplied to data-storage cabinets. The thermal coefficient of performance (COP_{th}), which describes the ratio Q_L/Q_H (cf. Figure 3a), is on the order of 0.6. However, the more relevant quantity in the context of waste-heat usage is the electrical COP (COP_{el}), which describes the ratio Q_L/W_E , where W_E is the electricity consumption of the system. Compared with mechanical compression chillers, which are normally used to provide datacenter cooling, adsorption-chiller systems in the field have a COP_{el} that is at least twice as high. In other words, the electricity consumption for the cooling infrastructure is at least halved as a result of the switch from compression chillers to waste-heat-driven adsorption chillers, which is enabled by the implementation of heat sinks with low exergetic losses.

Conclusions

The physics of miniaturization has essentially determined the roadmap for the success of the semiconductor industry for more than 50 years, and now several emerging trends highlight that advances in computing technology are not just restricted to the chip. For example, the disparity in transistor scaling and the interconnectivity at the chip edge have triggered the need for alternative power-delivery approaches. The same holds true for novel chip architectures relying on 3D packaging. Further, the unabated increase in chip-level power dissipation for computationally intensive systems calls for high-performance cooling solutions that minimize thermal resistance. A co-design of power-delivery and heat-dissipation structures appears essential to fully support the scalability of computing resources and interconnects for data transmission. Finally, with the cost of purpose-built

computing hardware dropping and concerns about resource utilization increasing, the energy efficiency of computing systems has become increasingly important. As discussed herein, it is clear that to address these challenges holistically, various physical principles need to be applied to the world of computing at various length scales. There still is ample opportunity for innovation and scientific exploration across many disciplines to advance computing.

References

- Andersen, T. M., Krismer, F., Kolar, J. W., Toifl, T., Menolfi, C., Kull, L., Morf, T., Kossel, M., Brändli, M., Buchmann, P., Francese, P. A. (2014). A Sub-ns Response On-Chip Switched-Capacitor DC-DC Voltage Regulator Delivering 3.7 W/mm² at 90% Efficiency Using Deep-Trench Capacitors in 32 nm SOI CMOS. In *IEEE International Solid-State Circuits Conference 2014* (pp. 90–91).
- Aristov, Y. (2014). Concept of adsorbent optimal for adsorptive cooling/heating. *Applied Thermal Engineering*, 72(2), 166–175.
- Borkar, S. (2013). Role of interconnects in the future of computing. *Journal of Lightwave Technology*, 31(24), 3927–3933.
- Borkar, S., & Chien, A. A. (2011). The future of microprocessors. *Communications of the ACM*, 54(5), 67–77.
- Brunschwiler, T., Michel, B., Rothuizen, H., Kloter, U., Wunderle, B., Oppermann, H., & Reichl, H. (2008). Interlayer cooling potential in vertically integrated packages. *Microsystem Technologies*, 15(1), 57–74.
- Brunschwiler, T., Paredes, S., Drechsler, U., Michel, B., Cesar, W., Leblebici, Y., Wunderle, B., Reichl, H. (2010). Heat-removal performance scaling of interlayer cooled chip stacks. *12th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*.
- Brunschwiler, T., Schlottig, G., Ni, S., Liu, Y., Goicochea, J. V., Zürcher, J., & Wolf, H. (2012). Formulation of percolating thermal underfills using hierarchical self-assembly of micro- and nanoparticles by centrifugal forces and capillary bridging. *International Microelectronics and Packaging Society (IMAPS)*, 749–759.
- Brunschwiler, T., Smith, B., Ruetsche, E., & Michel, B. (2009). Toward zero-emission data centers through direct reuse of thermal energy. *IBM Journal of Research and Development*, 53(3), 1–13.
- Chang, L., Montoye, R. K., Ji, B. L., Weger, A. J., Stawiasz, K. G., & Dennard, R. H. (2010). A fully-integrated switched-capacitor 2:1 Voltage converter with regulation capability and 90% efficiency at 2.3A/mm². *IEEE Symposium on VLSI Circuits, Digest of Technical Papers*, 55–56.
- Davis, J. A., Venkatesan, R., Kaloyeros, A., Beylansky, M., Sour, S. J., Banerjee, K., Saraswat, K.C., Rahman, A., Reif, R., Meindl, J. D. (2001). Interconnect limits on gigascale integration (GSI) in the 21st century. *Proceedings of the IEEE*, 89(3), 305–324.
- Dennard, R. H., Gaensslen, F. H., Yu, H.-N., Rideout, V. L., Bassous, E., & Andre R. LeBlanc. (1974). Design of ion-implanted MOSFET's with very small physical dimensions. *IEEE Journal of Solid-State Circuits*, 9(5), 256–268.
- ENERGY STAR Score for Data Centers in the United States. (2014). Retrieved from https://www.energystar.gov/sites/default/files/tools/Data_Centers.pdf. Last accessed 08.02.2016.
- Erdmann, C., Lowney, D., Lynam, A., Keady, A., McGrath, J., Cullen, E., Breathnach, D., Keane, D., Lynch, P., De La Torre, M., De La Torre, R., Lim, P., Collins, A., Farley, B., Madden, L. (2014). A heterogeneous 3D-IC consisting of two 28 nm FPGA die and 32 reconfigurable high-performance data converters. *IEEE Journal of Solid-State Circuits*, 50(1), 258–269.
- Escher, W., Michel, B., & Poulikakos, D. (2010). A novel high performance, ultra thin heat sink for electronics. *International Journal of Heat and Fluid Flow*, 31(4), 586–598.
- Khurshid, M. J., & Lipasti, M. (2013). Data compression for thermal mitigation in the hybrid memory cube, *IEEE 31st International Conference on Computer Design, (ICCD)* (pp. 185–192).
- Kjeang, E., Proctor, B., Brolo, A., Harrington, D., Djilali, N., & Sinton, D. (2007). High-performance microfluidic vanadium redox fuel cell. *Electrochimica Acta*, 52(15), 4942–4946.
- Knickerbocker, J., Andry, P., Dang, B., Horton, R., Interrante, M., Patel, C., Polastre, R. J., Sakuma, K., Sirdeshmukh, R., Sprogis, E. J., Sri-Jayantha, S. M., Stephens, A. M., Topol, A. W., Tsang, C. K., Webb, B. C., Wright, S. L.. (2008). Three-dimensional silicon integration. *IBM Journal of Research and Development*, 52(6), 553–569.
- Koomey, J. G. (2011). Growth in Data Center Electricity Use 2005 To 2010. Retrieved from <http://www.koomey.com>. Last accessed 08.02.2016.
- Meijer, G. (2010). Cooling Energy-Hungry Data Centers. *Science*, 328(5976), 318.
- Moore, S., & Greenfield, D. (2008). The next resource war: computation vs. communication. *Proceedings of the 2008 International Workshop on System Level Interconnect Prediction*, 81–85.
- Nowak, E. (2002). Maintaining the benefits of CMOS scaling when scaling bogs down. *IBM Journal of Research and Development*, 46(2), 169–180.
- Pratt, A., & Kumar, P. (2007). Evaluation of Direct Current Distribution in Data Centers to Improve Energy Efficiency. *The Datacenter Journal*, (March).
- Ramm, P., Klumpp, A., Weber, J., & Taklo, M. M. V. (2010). 3D System-on-Chip technologies for More than Moore systems. *Microsystem Technologies-Micro-and Nanosystems-Information Storage and Processing Systems*, 16(7, SI), 1051–1055.
- Roy, K., Mukhopadhyay, S., & Mahmoodi-Meimani, H. (2003). Leakage Current Mechanisms and Leakage Reduction Techniques in Deep-Submicrometer CMOS Circuits. *Proceedings of the IEEE*, 91(2), 305–327.
- Ruch, P., Brunschwiler, T., Escher, W., Paredes, S., & Michel, B. (2011). Toward five-dimensional scaling: How density improves efficiency in future computers. *IBM Journal of Research and Development*, 55(5), 15:1–13.
- Ruch, P., Ebejer, N., Sridhar, A., & Michel, B. (2015). Power delivery and thermal management of electronic packages using redox flow systems, *The International Flow Battery Forum (IFBF)*, Glasgow.
- Sabry, M. M., Sridhar, A., Atienza, D., Ruch, P., & Michel, B. (2014). Integrated microfluidic power generation and cooling for bright silicon MPSoCs. *Design, Automation & Test in Europe Conference & Exhibition (DATE)*, 1–6.
- Shah, A. J., Carey, V. P., Bash, C. E., & Patel, C. D. (2006). An Exergy-Based Figure-of-Merit for Electronic Packages. *Journal of Electronic Packaging*, 128(4), 360.
- Shah, A. J., Carey, V. P., Bash, C. E., & Patel, C. D. (2008). Exergy Analysis of Data Center Thermal Management Systems. *Journal of Heat Transfer*, 130(2), 021401.
- Shalf, J., Bashor, J., Patterson, D., Asanovic, K., Yelick, K., Keutzer, K., & Mattson, T. (2009). The MANYCORE Revolution: Will HPC LEAD or FOLLOW? *SciDAC Review*, Fall, 40–49.
- Skyllas-Kazacos, M., Chakrabarti, M. H., Hajimolana, S. a., Mjalli, F. S., & Saleem, M. (2011). Progress in Flow Battery Research and Development. *Journal of The Electrochemical Society*, 158(8), R55.
- Stanley-Marbell, P., Cabezas, V. C., & Luijten, R. (2011). Pinned to the walls: impact of packaging and application properties on the memory and power walls. *Proceedings of the 17th IEEE/ACM International Symposium on Low-Power Electronics and Design (ISLPED '11)*, 51–56.
- Tong, H. M., Lai, Y. S., & Wong, C. P. (2013). *Advanced Flip Chip Packaging*. New York: Springer, ISBN 978-1-4419-5768-9..
- Van Heddeghem, W., Lambert, S., Lannoo, B., Colle, D., Pickavet, M., & Demeester, P. (2014). Trends in worldwide ICT electricity consumption from 2007 to 2012. *Computer Communications*, 50(0), 64–76.
- Wang, Y., Chae, S. H., Dunne, R., Takahashi, Y., Mawatari, K., Steinmann, P., Bonifield, T., Jiang, T., Im, J., Ho, P. S. (2012). Effect of intermetallic formation on electromigration reliability of TSV-microbump joints in 3D interconnect, *Proceedings of the Electronic Components and Technology Conference (ECTC)* (pp. 319–325).
- Ziegler, F. (2009). Sorption heat pumping technologies: Comparisons and challenges. *International Journal of Refrigeration*, 32(4), 566–576.
- Zimmermann, S., Meijer, I., Tiwari, M. K., Paredes, S., Michel, B., & Poulikakos, D. (2012). Aquasar: A hot water cooled data center with direct energy reuse. *Energy*, 43(1), 237–245.
- Zürcher, J., Chen, X., Burg, B. R., Zimmermann, S., Hong, G., Studart, A. R., Potasiewicz, G., Warszynski, P., Brunschwiler, T. (2015). Enhanced thermal underfills by bridging nanoparticle assemblies in percolating micro-particle beds, *Proceedings of the International IEEE Conference on Nanotechnology (IEEE Nano 2015)* (pp. 577–580).
- Zürcher, J., Yu, K., Schlottig, G., Baum, M., Taklo, M. M. V., Wunderle, B., Warszynski, P., Brunschwiler, T. (2015). Nanoparticle assembly and sintering towards all-copper flip chip interconnects, *Proceedings of the Electronic Components and Technology Conference (ECTC)* (pp. 1115-1121)

Milestones in Physics (9)

The Long Search for Unconventional Superconductivity

T. Maurice Rice

1. Introduction

Superconductivity is undoubtedly the most spectacular effect in metals. The discovery that some metals upon cooling below a critical temperature, T_c , can enter a state that allows an electric current to flow without any resistance through a macroscopic dirty wire, was both astonishing and completely mysterious. But then the electrical properties of materials were not understood at all at the time of Kamerlingh Onnes' discovery in 1911. While the revolution in our understanding of the behavior of electrons in metals, semiconductors etc. came with quantum mechanics in the nineteen twenties, the new quantum mechanics failed to explain superconductivity, leading to much frustration, e.g. as recounted in Felix Bloch's recollections of his year at ETH in 1928/29 [1].

"Pauli thought that superconductivity was the only remaining matter of some interest in the theory of metals and I should get on with it to be finally done with all these 'dirt effects' [...] Once in a while I thought I had indeed found such states but it never took Pauli long to point out some error in the calculations. While he did not object to my approach he became rather annoyed at my continued failure to come out with the desired answer to such a simple question. [...] After the fog, which had so long enveloped the phenomenon, had begun to lift after many years, I could not resist reminding Pauli that the problem was not quite so easy to solve as he thought when he gave it to me. Since that time he had become more mellow - so much more in fact, that he agreed."

The theoretical understanding came only in 1956 with BCS theory. Bardeen, Cooper and Schrieffer [2] showed how even a weak electron-electron attraction generated at low energies by the exchange of phonons – the quanta of lattice vibrations, leads to a groundstate with a macroscopic quantum condensate of electron pairs. Single electrons obey the Pauli principle that forbids double occupancy of a state ruling out a single fermion condensate, but a pair of fermions is akin to a boson and bosons can form a macroscopic condensate, e.g. liquid ^4He . It is no exaggeration to say that BCS theory overnight turned superconductivity from the biggest unsolved mystery in solid state physics into the most successful microscopic theory in the field. In the years that followed, the many anomalous properties of superconductors were explained, not just qualitatively, but also with quantitative accuracy.

2. Conventional Superconductors described by BCS Theory.

The transition temperature, T_c , is one of the key properties determining the potential for applications of a superconductor. In BCS theory this is limited to a fraction of the characteristic Debye energy of the phonon spectrum. The electron-phonon coupling enters also in the formula for T_c , but this cannot be raised arbitrarily by increasing the strength

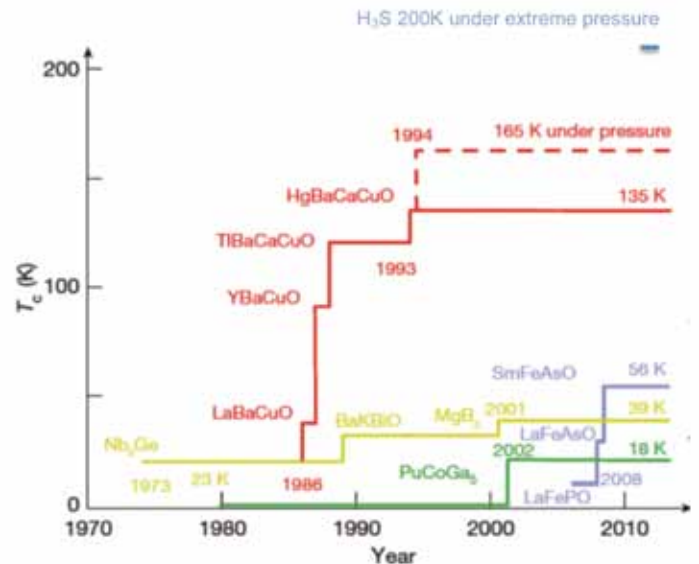


Fig. 1: The evolution of the maximum transition temperature in the most important superconductor families since 1970.

of the coupling. Such an increase is limited by the onset of a lattice instability to an alternative crystal structure, if the coupling becomes too strong. So for many years in spite of wide ranging searches, the maximum T_c was fixed at 23 K – the T_c of Nb_3Ge , see Fig. 1. Curiously BCS theory with its explicit formula for T_c , did not lead immediately to new superconductors with increased T_c . The skeptical response of the leading experimentalists can be seen in the exchange between Phil Anderson and Berndt Matthias [3] in 1964.



Phil Anderson and Berndt Matthias

The BCS formula predicted that the combination of high frequency phonons and enhanced electron-phonon interactions was the key to raising T_c . At the turn of the century Jun Akimitsu and his group [4] discovered superconductivity in MgB_2 with a $T_c = 39$ K, which almost doubled the record T_c in BCS superconductors. MgB_2 conforms perfectly to the BCS recipe for a high T_c , namely it has light B ions, which lead to high energy B-B stretching phonons. These in turn are coupled strongly to a small sheet of the Fermi surface formed by B $2p\sigma$ -bonding orbitals. Curiously this type of Fermi surface is very exceptional and so MgB_2 remains an isolated exception.

Very recently a new type of BCS superconductor with far higher T_c values was discovered by Drosdov et al. [5] through the application of exceptionally high pressure to hydrides. The underlying idea goes back to early work by Neil Ashcroft [6] who proposed that hydrogen could transform from the molecular solid into a metal under high pressure, leading to a metal with very high energy phonons causing high temperature superconductivity. Unfortunately a metallic state of hydrogen at high pressure has proved elusive. The very recent discovery has started with a sulfur hydride and reported a metallic state at very high pressure (~ 140 GPa) with vanishing resistivity at $T \sim 200$ K. Presumably, this is due to the formation of a metallic state containing high frequency vibrations involving predominantly H-ions. This exciting result establishes that BCS superconductivity is not limited to $T < 40$ K, but this particular example is clearly not suitable for applications in view of the very high pressures that are required to stabilize it.

3. Unconventional Superconductivity stabilized by Repulsive Interactions.

Although an electron-electron attraction is at the heart of BCS theory, the question was soon raised after its discovery, whether a macroscopic quantum electron pair condensate could be stabilized in some way using the dominant Coulomb repulsive interaction between electrons in metals. At the heart of BCS theory is the so-called gap equation, namely the self-consistent mean field equation for the amplitude of the condensed electron pairs at the Fermi surface. For attractive interactions, it is possible to construct a solution with an almost constant pairing amplitude around the Fermi surface for an electron pair in a spin-singlet state with opposite spins. But this pairing scheme fails for repulsive interactions. Several theorists realized early on that a different type of self-consistent solution to the gap equation is possible for repulsive interactions [7]. In this case one must allow for sign changes in the pairing amplitude around the Fermi surface and in addition one may relax the constraint of spin singlet pairing. These suggestions for overcoming the limitations of the electron-phonon mechanism were an additional motive driving the search for such an unconventional (i.e. non-BCS) superconductor. However, again progress was very slow and BCS theory continued to explain all known superconducting metals for many years.

Interest in unconventional (i.e. non-BCS) forms of pairing focused on the fermionic Helium isotope, ^3He . The more common bosonic isotope ^4He was well known as a superfluid below $T = 2$ K, but the very strong short range repulsion between He atoms led to speculation that the fermionic isotope would also undergo a transition into a superfluid state but likely at a much lower temperature. The discovery of a phase transition at $T \sim 1$ mK by Doug Osheroff and coworkers [8] in 1972 was soon followed by the identification of the low temperature phase as a superfluid with a pairing amplitude with p-wave symmetry and triplet parallel spin state. Many elegant and beautiful experiments followed, as the exotic physics of this ideal fermionic superfluid was uncovered.

This discovery verified the proposals for unconventional pairing between fermions with repulsive interactions but it

had no immediate effect on the search for metallic counterparts. There were suggestions that favorable conditions could occur in metals near the boundary to ferromagnetism, which could stabilize p-wave spin triplet pairing, analogous to the superfluid state of ^3He . Yet again, these searches yielded no positive results.

In the mid-1970s a new type of metal was found, consisting of rare earth/actinide ions embedded in a light atom matrix whose wide band conduction electrons hybridized weakly with the localized 4f & 5f states of these ions. The weak admixing of these two radically different electronic states gives rise to a narrow band of slowly moving electronic states near the Fermi energy. The small velocity means a large mass and the consequent strongly enhanced specific heat at very low T led to Klaus Andres, John Graebner and Hans-Rudolf Ott to identify CeAl_2 as new metallic compound in 1975. This new type of metal was later christened a heavy fermion metal. Actually these electronic states are not heavy in the standard meaning of the word, they are just slow – a much less glamorous name than their current name: heavy fermion metals.

A few years later in 1979, Frank Steglich and coworkers made the surprising discovery of a superconducting transition in another such heavy fermion metal, CeCu_2Si_2 . Soon other examples were found, e.g. UBe_{13} by Hans-Rudolf Ott and coworkers in 1981. Doubts that the superconducting transition was actually occurring in the heavy mass band were immediately answered by the exceptionally large specific heat anomaly at T_c . This proved that superconductivity was indeed occurring in the heavy mass band. In the intervening years many more examples have been found but almost always with single figure values of T_c . It was immediately obvious that this class of heavy fermion metals must be a very different type of metal to the conventional BCS superconductors whose Fermi level lies in the midst of broad electron conduction bands. It follows that a different mechanism must drive superconductivity in heavy fermion metals. This led to speculation that these would be unconventional superconductors, but identification of their exact symmetry is difficult. For more details and references, see the recent review by Zachary Fisk in Ref. [9].

Around the same time another set of exotic superconductors was discovered by Denis Jerome and Klaus Bechgaard, again unexpectedly. Their key components are large, generally planar, organic molecules, which form linear stacks or planar arrays. By choosing an appropriate mixture of donors and acceptors one can synthesize partially filled bands leading to metallic conductors. These have narrow energy bandwidths made from molecular states delocalized over the large molecules with weak intermolecular overlap. Although the intramolecular Coulomb repulsion is also weak, again it is the dominant interaction at low energy scales. This combination also favors unconventional forms of superconductivity, but here too, it is difficult to determine the exact unconventional symmetry of the superconductivity. Over the years a large number of organic superconductors have been discovered, almost all with low values of T_c , i.e. $T_c < 10$ K. More details can be found in the recent review by Denis Jerome in Ref [9].

4. High Temperature Superconductivity in the Cuprates driven by the Electron – Electron Interactions

The discovery with the strongest impact since the original discovery of Kamerlingh Onnes occurred decades later, when Georg Bednorz and Karl Alex Müller [10] reported superconductivity in a lightly doped cuprate insulator at an elevated temperature of 35 K. Their discovery immediately unleashed a frantic worldwide investigation of the cuprate compounds. Within a matter of months the transition temperature broke through the important milestone of 77 K – the temperature of liquid nitrogen. The highest value of T_c continued to climb rapidly before settling in at the current record of 133 K and even higher under pressure. These totally unprecedented values sparked great enthusiasm, even euphoria, about a forthcoming superconducting revolution with wide reaching consequences. This, of course as we all know now, did not materialize and superconducting technology remains a niche business. The discovery did however revolutionize our view of superconductivity. For more details see the recent review by Hans-Rudolf Ott in Ref [8].

The theoretical revolution was set in motion immediately after the publication of the Bednorz - Müller results by Phil Anderson [11], who postulated that a radically different mechanism was at work in these cuprates. He pointed out that the parent stoichiometric cuprates were Mott insulators, that is to say, their insulating character arises not from an energy gap between filled and empty Bloch bands, but from a dominant Coulomb repulsion between the electrons in the half-filled highest Bloch band. This is made from 3d-Cu orbitals strongly admixed with 2p-O orbitals as illustrated in Fig. 2. In this insulating state the Cu-ions have just one electron missing in their 3d-shell and this hole takes on a spin $S = 1/2$ character. The spins on neighboring Cu-ions are strongly coupled antiferromagnetically, i.e., antiparallel. According to quantum mechanics this leads to an exceptionally strong bond when two $S = 1/2$ spins combine into a singlet ($S = 0$) groundstate. In the simplest version such pairs are present, at least virtually, in the groundstate, becoming mobile only when the number of electrons/site in the lattice is reduced from the integer value. The result is a quantum state, which contains a macroscopic condensate of electron pairs as in

BCS theory, but with the crucial difference that the state of relative motion of the pairs is generally believed not to be a simple s-wave state (i.e. zero angular momentum) but rather a d-symmetry [$\sim (\cos k_x - \cos k_y)$] form. This important difference in the internal motion of the pairs supported by a series of elegant experiments, which directly probed the angular dependence of the phase of the pair condensate in \mathbf{k} – space [12]. Such a clear difference in the pairing symmetry rules out simple electron-phonon driven pairing since that as remarked above, this always stabilizes s-wave pairing. However not all are convinced, e.g. see the recent article by Karl Alex Müller in the July 2015 issue of this journal, which argues for s-wave symmetry.

This is not the place for a review of the vast literature on the electronic properties of the cuprates that increases down to the present day. But perhaps it is worthwhile to comment on why it has proved so difficult to develop a complete and generally accepted microscopic theory for the electronic properties of cuprates. This contrasts sharply with the case of MgB_2 where, as discussed above, a broad consensus on the theory underlying the high T_c was soon reached. In a way this lack of consensus is surprising since all the cuprate superconductors are variations on the same theme, namely square CuO_2 -planes with the Cu-ions lightly doped away from a Cu^{2+} -oxidation state. The various families of cuprate compounds differ only in the content of the spacer layers separating the CuO_2 -planes. In fact the underlying model stripped down to its essentials, takes the apparently simple form of fermions moving in a single band with a strong short range repulsion [13]. This apparent simplicity is deceptive since this model is truly a strong coupling many body problem. Its fermionic character makes direct numerical simulation extremely challenging.

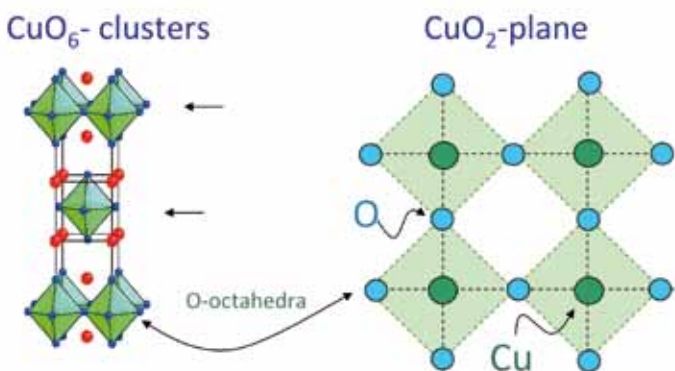
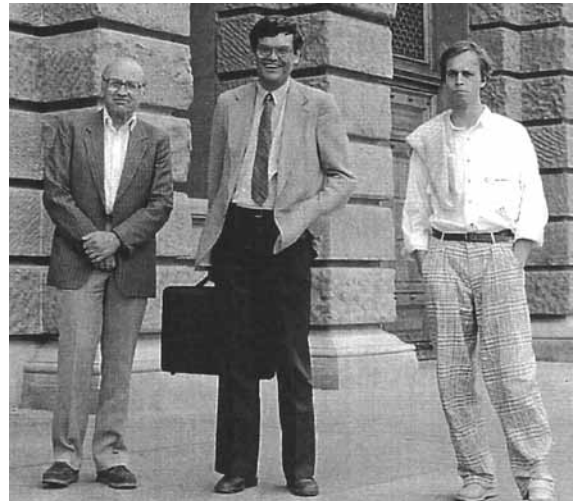


Fig. 2: The 3D structure of a typical cuprate consists of layers of CuO_6 octahedra arranged so as to form a square planar lattice. In the CuO_2 layers, the Cu ions take the oxidation state Cu^{2+} - a $S = 1/2$ -ion with an electron missing from the uppermost hybridized Cu-O orbital. Chemical doping reduces the electron count in the band formed by these states slightly away from 1 electron per CuO_4 plaquette. The resulting manybody Hamiltonian takes the form of a single band Hubbard model.



Walter Kohn, T. M. Rice and his graduate student Claudius Gros who wrote an excellent thesis in the early days (Picture from 1988)

Actually the main controversies are not over the superconductivity per se. In the higher doping region, generally referred to as the overdoped region, the superconductivity appears rather usual, apart from the question of the pairing symmetry as discussed earlier. The underlying Fermi surface agrees well with 'a priori' estimates based on density functional theory and T_c rises continually as the density of doped holes is decreased below the starting threshold. The

controversial debate concerns the relative importance of the onsite repulsion and antiferromagnetic spin fluctuations, analogous to the phonons in BCS superconductors, in driving the pairing interaction.

The cuprates are extreme Type II superconductors, which means that magnetic vortices enter already at very small magnetic fields. This has stimulated a major and successful effort to extend the phenomenological description of the vortex fluid to understand the interplay of enhanced dynamic fluctuations, both thermal and quantum, and static disorder. A comprehensive account of this work can be found in the review by Gianni Blatter and collaborators [14].

As the doped hole density is further lowered, T_c goes through a maximum and radical changes appear in the electronic properties of these underdoped cuprates. The most radical one is the breakup of the Fermi surface observed in Angle Resolved Photoemission. The full Fermi surface at overdoping splits into 4 separate Fermi arcs without an underlying broken translational symmetry. This behavior is consistent with a transition into a precursor to the Mott state, where a full charge gap eliminates the Fermi surface entirely. This highly unusual situation is accompanied by other anomalies, e.g. a large expansion of the temperature range of superconducting fluctuations at $T > T_c$. It follows that we need a truly novel nonperturbative solution of this strongly coupled fermionic problem. The result is a formidable theoretical challenge, which so far has evaded any consensus. Again more details can be found in Hans-Rudolf Ott's review in Ref. [8].

Yet another difficulty arises from the complexity of these cuprate compounds taken as a whole, although the active element of the lightly doped CuO_2 -planes is relatively simple. This complexity can cause experimental glitches, which may be unimportant for the actual superconductivity, but can act to confuse matters. In the end we want to have a complete microscopic theory that simultaneously describes all the exotic phenomena that these cuprates display.

All available techniques have been employed in the experimental investigations. In many cases specific techniques are limited to a small subset of the many cuprates. This makes the reconciliation of all experimental results into a single theoretical framework indeed a formidable task. The temptation to declare victory after achieving agreement with a single set of experiments has often proven to be too great to resist.

5. Other Superconducting Transition Metal Compounds.

The number of superconducting transition metal compounds, which are candidates for electron - electron driven superconductivity, is disappointingly small. These candidate compounds have larger bandwidths and higher energy scales, which are responsible for their higher T_c values. So it was a pleasant surprise when a new system was found a few years ago, namely the Fe-pnictides [15]. These compounds have certain similarities to the cuprates. They are also planar compounds, in this case the active ingredients are FeAs layers. These layers also show antiferromagnetic order in the stoichiometric compounds and become superconducting only upon doping. There are however significant

differences to the cuprates. The stoichiometric compounds are often semimetals, not Mott insulators, which points to intrinsically weaker interactions between the conduction electrons. The exact symmetry of the superconducting pairing is still not definitively determined, but most likely not simple s-wave. The range of the transition temperatures is roughly a factor of 3 smaller than in the cuprates, but still much too large to be explained by the electron - phonon interactions. These are estimated to be quite weak in these compounds. So the proposal that superconductivity here is also driven by the electron - electron interactions, is quite persuasive.

A third transition metal compound that also belongs to this class is Sr_2RuO_4 [16]. Again this is a layered compound with important similarities and differences to the cuprates. The important element is a RuO_2 -plane but now this is metallic and superconducting at stoichiometry and superconductivity is quickly destroyed by even weak disorder. The pairing symmetry here is believed to be triplet p-wave, analogous to the case of ^3He discussed earlier. Actually, this difference is consistent with the differences in the electronic structure to the cuprates. This pairing symmetry has many fascinating consequences, which make Sr_2RuO_4 a very special superconductor, but the very low T_c rules out almost all practical applications.

The fact that only a small number of transition metal compounds display electron-electron driven superconductivity is disappointing. It contrasts with the two other superconductor classes with strongly interacting conduction electrons that we discussed earlier – the heavy fermion and organic metallic compounds. These systems apparently demonstrate that superconductivity driven by electron - electron interactions should not be a rare phenomenon. Rather it is a form of ordered electronic state on a par with magnetic and charge ordering, when the interaction strength is comparable to the bandwidth. Yet it remains a very rare occurrence in the transition metal compound metals. The answer to this dilemma, I believe, lies in unwanted consequences that come with expanding the electronic bandwidth to get a higher T_c . At the same time, the larger bandwidths increase the magnitude of the contribution that the conduction electrons make to the total groundstate energy. But a compound always chooses the lattice symmetry that minimizes the total energy. This is often a low symmetry crystal, which locally distorts the local coordination of the structure around the transition metal element to achieve the minimization of the total energy. We see examples of this when we compare cuprates with transition metal oxides made from elements at the other end of the transition metal series from copper. Vanadium and titanium form oxides with a single electron in the 3d-band. But now the 3d-electronic states are those, which are weakly hybridized with the 2p-orbitals of the oxygen ions in the octahedral cage surrounding the transition metal ion. This leads to strong low symmetry distortion of the octahedral cage which distorts when the local charge changes, e.g. $1 \rightarrow 2$ or $1 \rightarrow 0$ electrons on the ion. This, in turn, leads for fractional valence compounds to form low symmetry structures with tendencies to local charge differentiation according to the valence state. The result is complex ordered charge structures that mostly are not metallic at low temperatures, such as typically found in titanates and vanadates.

If we compare a typical transition metal compound to the cuprates, we find the exceptional property of a cuprate is its high symmetry square planar lattice with the same local symmetry for both Cu^{2+} and Cu^{3+} valences – see Fig. 2. This in turn means that a doped hole with Cu^{3+} valence is not surrounded by a deep lattice distortion, which would greatly restrict its mobility. The quantum nature of the hole doped CuO_2 planes is emphasized by this combination of the low spin, $S = \frac{1}{2}$, of the Cu^{2+} valence state, which has strong antiferromagnetic coupling to its nearest neighbor spins. All of these properties combine to strengthen intrinsic quantum nature of the conduction electron fluid and of course, superconductivity is a purely quantum phenomenon. The uniqueness of the cuprates among transition metal oxides illustrates the key hurdle is not really finding a low energy effective Hamiltonian, rather it is synthesizing a real material that realizes the desired effective Hamiltonian at low energy scales.

6. Outlook

There is still the open question of whether it is possible to manipulate the cuprates in some way, which will enhance T_c further. In the case of semiconductors, novel physics and novel applications have come from the synthesis of artificial structures. The technology of growing artificial structures in transition metal oxides lags far behind that in semiconductors. The shorter length scales in the oxides will not make the task easier. But the biggest hurdle may be the lack of a convincing idea of how one could modify the cuprates in a way leading to a raised T_c .



T. M. Rice

There are some trends that give hints to possibilities that would increase T_c . For example, one knows that increasing the number of layers in multilayer compounds enhances T_c , at least initially. The highest T_c in all of the cuprates has been achieved in the Hg - cuprate family. These can be grown as n-multilayer compounds up to $n = 7$ closely spaced CuO_2 layers. T_c rises initially presumably due to interlayer coupling but this rise saturates at $n = 3$ and T_c drops with for higher values of n [17]. This drop has been ascribed to substantial decreases in the hole doping in the inner layers for $n > 3$. If this drop could somehow be compensated, maybe an increase in T_c could be achieved. However, it would likely be only a modest increase.

Structuring the CuO_2 layers is another approach, which is worth consideration. For example, it is possible to modify the CuO_2 layers to Cu_2O_3 that consist of weakly coupled ladders with Cu-O-Cu rungs thereby enhancing the singlet binding energy between the Cu spins on a rung. However to date it has not proved possible to synthesize uniformly doped compounds with directly analogous to the superconducting cuprates with lightly doped CuO_2 square planar layers. It is not at all clear that such structuring will help. Indeed one might well argue that the high symmetry of the square planes combined with the $S = \frac{1}{2}$ spins enhances the quantum nature through its high symmetry. Since superconductivity is inherently quantum mechanical, such modifications that lower the symmetry, may turn out to be detrimental.

Finally, while there has been substantial progress in raising T_c the quest for a working room temperature superconductor is far from realization. The main obstacle lies not in proposing a model Hamiltonian, which could deliver such a superconductor, rather it is finding a compound with such a low energy Hamiltonian. The connection between the solid state chemistry that determines the crystal structure and hence the electronic structure, and the low energy effective Hamiltonian is too rigid to allow the synthesis of a theoretical proposal to be simply realized.

References

- [1] Bloch F., *Proc. Roy. Soc. Lond.* **A 371**, 24-27 (1980)
- [2] Bardeen, J., Cooper, L. N. & Schrieffer, J. R., *Phys. Rev.* **108**, 1175 (1957)
- [3] Anderson, P. W. & Matthias, B. T., *Science* **144**, 373–381 (1964)
- [4] Nagamatsu, J., Nakagawa, N., Muranaka, T., Zenitani, Y. & Akimitsu J., *Nature* **410**, 63–64 (2001)
- [5] Drozdov, A. P., Eremets, M. I., Troyan, I. A., Ksenofontov, V. & Shylin, S. I., *Nature* **525**, 73–76 (2015)
- [6] Ashcroft, N. W., *Phys. Rev. Lett.* **21**, 1748 (1968)
- [7] For a review of the early history of superconductivity thru' repulsion, see Anderson, P. W., *Int. J. Mod. Phys.* **B 20**, 3983-3998 (2010)
- [8] Osheroff D. D. et al., *Phys. Rev. Lett.* **28**, 885 (1972) & **29**, 920 (1972)
- [9] Superconductivity in New Materials, ed. Z. Fisk & H. R. Ott; *Contemporary Concepts of Condensed Matter* Vol. 4, Elsevier 2011
- [10] Bednorz, J. G. & Müller, K. A., *Z. Physik* **B 64**, 189–193 (1986)
- [11] Anderson, P. W., *Science*, **235**, 1196 – 1198 (1987)
- [12] Tsuei, C. C. & Kirtley, J., *Rev. Mod. Phys.*, **72**, 969 (2000)
- [13] Zhang, F. C. & Rice, T. M., *Phys. Rev.* **B 37**, 3759-3761 (1988)
- [14] Blatter G., Feigelman M. V., Geshkenbein V. B., Larkin A. I. and Vinokur V. B., *Rev. Mod. Phys.* **66** 1125 (1994).
- [15] Kamihara, K. Y., Watanabe, T., Hirano, M. & Hosono, H., *J. Am. Chem. Soc.* **130**, 3296–3297 (2008)
- [16] Maeno Y., Rice T. M. and Sigrist M., *Physics Today* **54** 42 (2001)
- [17] Mukuda, H., Shimizu, S., Iyo, A. & Kitaoka, Y., *J. Phys. Soc. Jap.* **81**, 011008 (2012)

Plenary Talks

We continue the series of plenary talks of our joint annual meeting 2015 in Vienna.

Molecular structure identification of single molecules on thin insulating films

PT 6/2015

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The quest for pushing the resolution in scanning probe microscopy forward to the atomic scale has been a driving factor since the invention of the scanning tunneling microscope (STM) [1] and the atomic force microscope (AFM) [2]. Recently, noncontact AFM was used to resolve the structure of an individual molecule with atomic precision [3]. A crucial factor to increase the lateral resolution was to use a functionalized tip, which is a deterministic chemical modification of the last atoms of the scanning probe tip. The tip can be functionalized by atomic manipulation, that is picking up a specific adsorbate from the sample surface [4, 5]. Importantly, the atomic/molecular functionalizations yield the predominant force contributions for the interaction on the atomic scale [6]. The most widely used tip functionalization for high-resolution AFM to date is a single CO molecule [3].

For any interpretation of AFM data, understanding of the contrast mechanism is crucial. At first glance, the atomically resolved AFM images as the one shown in Fig. 1a being similar to the molecular structure, suggest that the contrast simply reflects the geometry of the molecule. However, the imaging mechanism is far from being simple. First, the AFM signal is composed of several different types of interactions, such as electrostatic forces, van der Waals attraction, chemical bond formation, and Pauli repulsion. Additionally, as these forces act on very different length scales, different parts of the tip and sample structure may contribute to the imaging process. Density functional theory (DFT) is a crucial tool to separate different force contributions in order to understand the imaging mechanism. It could be shown that Pauli repulsion is responsible for the atomic contrast observed in AFM images and the long-ranged van der Waals and electrostatic forces compose the attractive background [6].

An important effect to account for are possible tip relaxations. Specifically, tilting of CO and other terminations occur because of lateral forces, which critically affects the image contrast [7 - 9]. CO tilting leads to a sharpening of the bonds and distorts the apparent molecule structure, which can also be exploited to differentiate the bond order of individual bonds in molecules [7].

To study compounds on a single molecule basis with scanning probe techniques requires to work at ultrahigh vacuum and low temperatures (typically 4 K). As a sample we use a Cu(111) single crystal partly covered by micrometer-sized two-monolayer thick NaCl islands. In recent years, such ultrathin insulating films on metal substrates have gained appreciable attention as templates for the study of individual adsorbates [10 - 12]. This attention stems from both the decoupling of the adsorbate electronic states from the metal substrate and the weak adsorbate-film interaction, which

makes it possible to study single molecules and atoms close to their native state.

The identification of molecular structures is an important emerging application of high-resolution molecular imaging by AFM with functionalized tips. Recently, AFM was used in combination with conventional techniques (i.e nuclear magnetic resonance and mass spectrometry) for the structure elucidation of natural compounds [13, 14] and to identify reaction products formed by on-surface chemistry [15] and by atomic manipulation [16]. In the following we briefly review two of our recent studies: (i) an example where we analyzed a mixture of molecules present in petroleum [17] and (ii) a sequence of single-molecule reactions induced by atomic manipulation [18].

A strength of AFM is that single molecules can be addressed. This renders possible to investigate also samples that are mixtures of molecules and to identify their structures individually. Petroleum is probably the most prominent natural mixture and one of the most complex materials encountered with possibly over 100,000 distinct chemical constituents [19]. A very enigmatic fraction of petroleum is asphaltene that is defined by a solubility classification that covers essentially the solid component of crude oil. Because of their

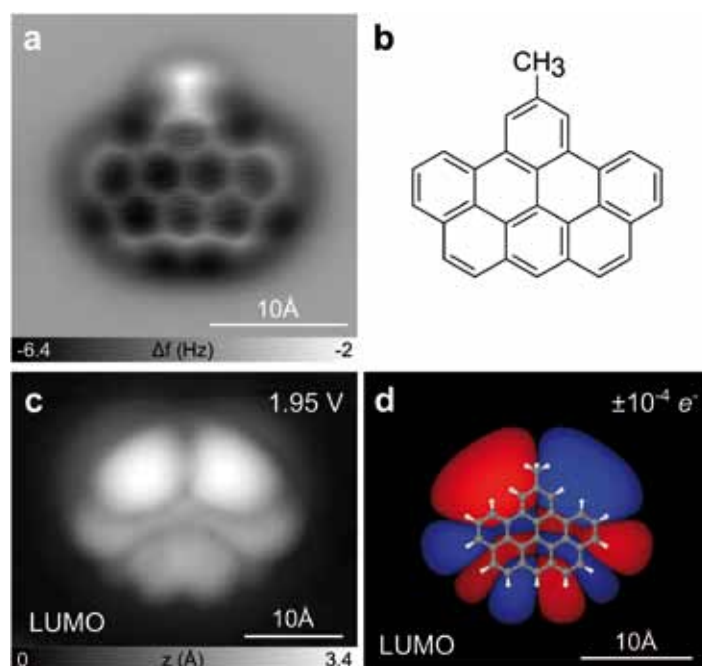


FIG. 1. *Asphaltenes*. **a**: AFM image of an asphaltene molecule revealing the structure. **b**: Structure hypothesis from **a**. **c**: STM orbital image of the lowest unoccupied molecular orbital (LUMO). **d**: Density functional theory calculation of the LUMO of **b**. Adapted with permission from Schuler et al. [17]. © 2015 American Chemical Society.

complexity, asphaltenes are posing an exceptional challenge for structure analysis. Although immense financial efforts are taken to learn about this substance as a matter of its economic relevance, even the most basic properties such as the mean molecular weight or molecular architecture have been under debate since years.

In our approach we used high-resolution AFM and STM to measure the atomic structure [3] and molecular orbitals [12] of individual asphaltene molecules. In Fig. 1a an AFM image of a molecule found in the asphaltene mixture is shown. In simple cases like here we can directly assign its structure from such an image (see Fig. 1b). When the molecule is located on an insulating NaCl island it is possible to access its frontier molecular orbitals by tuning the sample voltage such that electrons tunnel resonantly through the lowest unoccupied molecular orbital (LUMO) or the highest occupied molecular orbital (HOMO). A STM orbital image of the LUMO resonance of the molecule in Fig. 1a is shown in Fig. 1c. STM orbital imaging provides valuable complementary information about the molecule structure. The orbital images reflect an isosurface of the respective orbital as depicted in Fig. 1d. In this way the orbital images provide an independent cross-check of the structure assignment.

In the more than 100 atomically-resolved AFM images of individual asphaltene molecules we observed a tremendous diversity of different structures. The asphaltenes consist of a central aromatic core composed of generally one and sometimes a few polycyclic aromatic hydrocarbons and some aliphatic side-groups attached that can vary in their abundance and length depending on the sample origin and possible hydroprocessing. From such measurements, one can learn about the mixture characteristics and potentially gain a better understanding of physicochemical processes involved in petroleum processing.

The demonstrated structure elucidation of mixtures could also be viewed as a paradigm shift for the development of new molecules, as it makes the time-consuming synthesis and purification of tailored molecules redundant. Rather, many molecules can be screened in a single preparation.

A focal interest in chemistry is not only to analyze reaction products but also to understand reaction pathways. Reactive intermediates are involved in most chemical transformations. However, their characterization is a great challenge

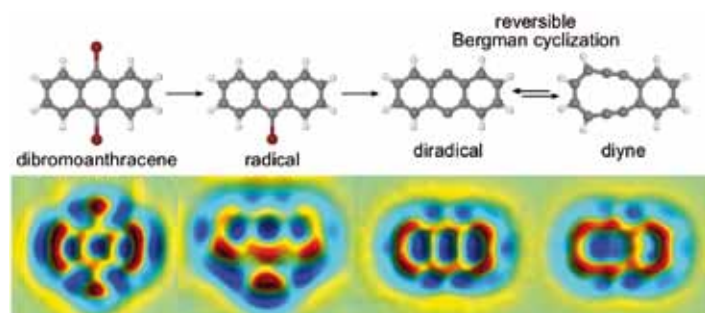


FIG. 2. Bergman cyclization. Top row: Chemical structures of the reaction products formed by successive STM-induced debromination of dibromoanthracene and subsequent retro-Bergman cyclization. Bottom row: AFM images of the respective reaction intermediates and products. Reprinted from Schuler et al. [18] with permission from Macmillan Publishers Ltd: *Nature Chemistry*, © 2015.

because of their short lifetime and high reactivity. The thin insulating NaCl film allows us to stabilize these reactive intermediates at cryogenic temperatures [16]. Still, their reactivity remains preserved even at low temperatures as proven by the ability to undergo different on-surface reactions triggered by atomic manipulation [16].

We could demonstrate the sequential derivation of diyne by three single-molecule reactions starting from dibromoanthracene (DBA) by means of atomic manipulation (see Fig. 2). The reaction intermediates and product could be identified and characterized by atomic resolution AFM measurements and STM orbital imaging that are compared with DFT calculations. Starting from DBA, two Br atoms could be cleaved from the molecule by applying voltage pulses with the tip to form a *para*-aryne diradical. In a last step, the diradical could be transformed into a highly-strained diyne molecule, which represents a so-called retro-Bergman cyclization. Interestingly, this reaction was reversible and we could trigger switching between diradical and the two possible diyne topomers, constituting a tri-state molecular switch. Thus, we demonstrate the creation and annihilation of an intramolecular C - C bond by atomic manipulation. DFT calculations reveal that upon this switching also the spin multiplicity is switched between a spin-singlet (diyne) and a spin-triplet (diradical) ground state [18], implying a change of the molecule's reactivity, optical and magnetic properties.

High-resolution noncontact-AFM and STM are valuable tools to gain insights into matter on the atomic scale. Specifically, we exploited the contrast enhancements provided by functionalized tips. The opportunity to study the structure of molecules and their properties on a single-molecule level offers exciting new ways to explore atomic-scale processes in molecular systems.

- [1] G. Binnig, H. Rohrer, C. Gerber, E. Weibel, *Appl. Phys. Lett.* **40**, 178 (1982).
- [2] G. Binnig, C. F. Quate, C. Gerber, *Phys. Rev. Lett.* **56**, 930 (1986).
- [3] L. Gross, F. Mohn, N. Moll, P. Liljeroth, G. Meyer, *Science* **325**, 1110 (2009).
- [4] L. Bartels, G. Meyer, K.-H. Rieder, *Appl. Phys. Lett.* **71**, 213 (1997).
- [5] F. Mohn, B. Schuler, L. Gross, G. Meyer, *Appl. Phys. Lett.* **102**, 073109 (2013).
- [6] N. Moll, L. Gross, F. Mohn, A. Curioni, G. Meyer, *New J. Phys.* **14**, 083023 (2012).
- [7] L. Gross, et al., *Science* **337**, 1326 (2012).
- [8] N. Moll, et al., *Nano Lett.* **14**, 61276131 (2014).
- [9] P. Hapala, et al., *Phys. Rev. B* **90**, 085421 (2014).
- [10] J. Repp, G. Meyer, F. E. Olsson, M. Persson, *Science* **305**, 493 (2004).
- [11] A. J. Heinrich, J. A. Gupta, C. P. Lutz, D. M. Eigler, *Science* **306**, 466 (2004).
- [12] G. Repp, G. Meyer, S. M. Stojkovic, A. Gourdon, C. Joachim, *Phys. Rev. Lett.* **94**, 026803 (2005).
- [13] L. Gross, et al., *Nature Chem.* **2**, 821 (2010).
- [14] K. O. Hanssen, et al., *Angew. Chem. Int. Ed.* **51**, 12238 (2012).
- [15] D. G. de Oteyza, et al., *Science* **340**, 1434 (2013).
- [16] N. Pavliček, et al., *Nat. Chem.* **7**, 623 (2015).
- [17] B. Schuler, G. Meyer, D. Peña, O. C. Mullins, L. Gross, *J. Am. Chem. Soc.* **137**, 9870 (2015).
- [18] B. Schuler, et al., *Nat. Chem.* (2015). DOI: 10.1038/NCHEM.2438.
- [19] O. C. Mullins, *Asphaltenes, Heavy Oils, and Petroleomics* (Springer, 2007).

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The development of safe, sustainable and environmentally friendly energy sources is one of the main challenges mankind faces in the 21st century. Fusion is based on the principle that powers the Sun and all stars in the universe, and it has the potential to provide a solution to the world's energy problem. Fusion is intrinsically safe, provides the largest energy density of all known energy production principles, uses fuels that are practically inexhaustible, does not produce greenhouse gases, does not require geological storage of wastes, and has no impact on weapon proliferation issues.

The basic challenge of fusion devices is to confine enough plasma, the ionized state of matter in which fusion reactions take place, at temperatures of 10-20 keV, for sufficiently long times. We focus here on the magnetic approach to fusion, in which the charged plasma particles are trapped in a cage formed by a magnetic field. We consider tokamak devices, which are based on a combination of fields produced by external coils and by a strong current driven by transformer action in the highly conducting hot plasma. To obtain electricity in a practical reactor, the fusion gain Q , the ratio of the power input to that produced by fusion reactions, must be significantly larger than 10. In Deuterium-Tritium plasmas this condition corresponds to $n\tau_E T > 10^{21}$ keVs/m³, where n and T are the plasma density and temperature, and τ_E is the energy confinement time.

When $Q > 5$, the self-heating due to the by-products of the fusion reactions provide the dominant contribution to the overall heating of the plasma. The plasma is said to be burning. In DT plasmas, the by-products are α -particles at 3.5 MeV, which transfer their energy to the background plasma by colliding with electrons and ions (Fig. 1). The understanding and control of burning plasmas constitute the focus of today's fusion research.

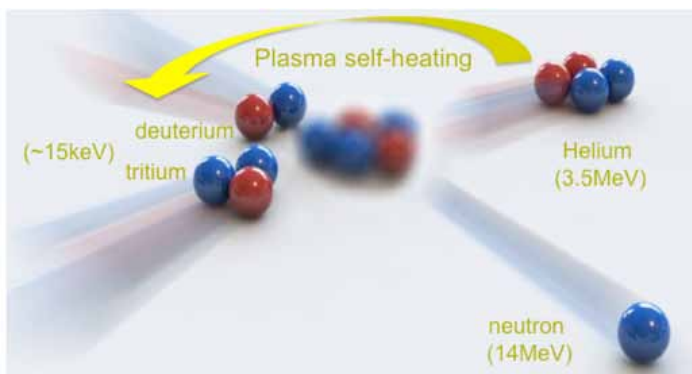


Fig. 1 The DT fusion reaction. The α particles must be confined in the plasma and transfer their energy by collisions to the DT ions, while the 14 MeV neutrons are used to generate heat from which electricity is produced, and to breed Tritium by reacting with Lithium in the blanket surrounding the plasma chamber.

First, it is necessary to reach the burning plasma conditions. This implies identifying auxiliary heating scenarios that can be used effectively in 50:50 DT mixtures, including neutral beam injection (NBI) and waves that resonate with the ion or electron cyclotron motion (Ion or Electron Resonance Heating, ICRH or ECRH). This also involves minimizing the ef-

fect of turbulence on the energy and particle confinement in the different regions of the plasma column.

Second, burning conditions must be sustained for macroscopic times by the auxiliary and self-heating processes. In the case of NBI and ICRH, as in that of the fusion generated α -particles, strong supra-thermal, or *fast* ions are created, with energies much greater than the mean bulk plasma energy [1]. As the fast ion slowing down process occurs over macroscopic time scales, good confinement is essential to obtain a high fusion power gain. In addition, as the fast ions carry large amounts of energy, only very minor ($< 5\%$) losses can be tolerated. This involves understanding and controlling their interactions with imperfections in the confining magnetic fields, with coherent waves with which they can resonate, and with turbulence. In turn, the fast ions influence the macroscopic plasma stability, an effect that must be regulated in order for the plasma to burn in stationary conditions.

Third, one has to restrain the interaction between the plasma and the surrounding material walls, while exhausting energy and particles from the burning plasma core, a major challenge towards the realisation of a nuclear fusion power plant [2]. In ITER, the first burning plasma device [3], whose aim is to demonstrate the scientific and technological feasibility of fusion, the plasma power to the walls will be of the order of 100 MW, resulting in heat fluxes of 10 MW/m² in the conventional configuration of the plasma periphery, the so-called magnetic divertor. This is at the limit of the capabilities of all present materials. The DEMO device [4], which will follow ITER to demonstrate that fusion can be deployed commercially, will need to have a size similar to ITER, for economical reasons, but higher exhaust power. Therefore, if conventional boundary configurations are used, the materials' limits will be exceeded. Alternative advanced solutions for the plasma periphery must therefore be found. An example of these is the snowflake divertor, pioneered on the TCV tokamak (Fig. 2). To be considered for DEMO, solutions like the snowflake divertor need to be proven viable

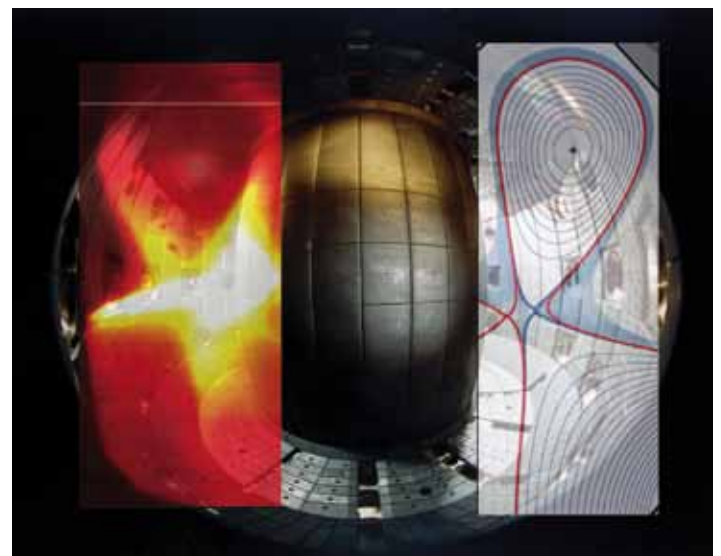


Fig. 2 The snowflake divertor in the TCV tokamak [5]

both from the point of view of plasma conditions and from that of the engineering design compatibility with reactor constraints, such as the need for a large fraction of power from the plasma in the form of isotropic radiation, and that of suppressing violent instabilities that can be driven by the extreme plasma gradients at its periphery. Wall materials must avoid significant Tritium retention and dust production, and be compatible with a core plasma that has only traces of high atomic number materials.

Finally, high performance burning plasmas must be achieved in conditions that optimize plant operation, with for example an effective Tritium breeding and burn-up, an adequate thermo-dynamical efficiency and a high degree of plant reliability and availability.

A key feature of burning plasmas is that alpha particles will couple several plasma features, including macroscopic stability, wave-particle interactions and transport, which will complicate the interplay between plasma dynamics and external systems (Fig. 3).

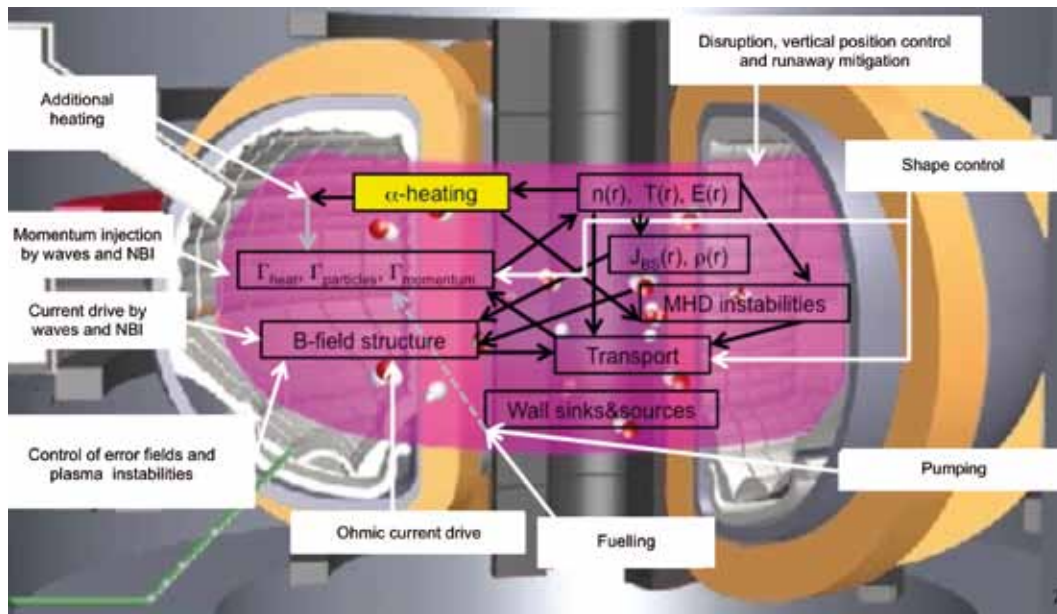


Fig. 3 Interplay between plasma dynamics and external systems. The letter Γ indicates a flux, while E is the electric field and J_{BS} is the self-generated bootstrap plasma current.

The challenges of simulating burning plasmas reflect those that characterize experimental research. As fusion plasmas are complex self-organized systems with an extremely wide range of spatial and temporal scales, we must improve our understanding of the individual phenomena occurring in a confinement device, but also integrate these different elements into a comprehensive description, so as to provide a solid modeling basis for how to reach, maintain and control burning plasma conditions.

The complexity of the individual phenomena and of the non-linear coupling between them calls for using different physical models (kinetic, gyro-kinetic, fluid) for representing the different plasma regions, and for simulations that exploit the most advanced numerical techniques, and necessitating state-of-the-art high performance computers (see Fig. 4).

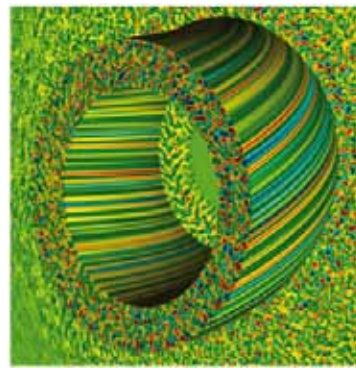


Fig. 4 Contours of perturbed density of a global gyro-kinetic turbulence simulation with the ORB5 code in an ITER tokamak plasma configuration on PetaFlop HPC (10^9 particles, 10^9 points, $\sim 10^6$ CPU hours) [6].

Both in the experiments and simulation efforts, significant progress has indeed been achieved on the separate building blocks of the diagram in Fig. 3, but the coupling of the different elements makes extrapolations from the weakly self-heated plasmas that are available today difficult and may lead to new phenomena. For this reason, the whole community is looking forward to the first burning plasmas obtained in the ITER device, which is under construction in the South of France (Fig. 5), and in which a single $Q = 10$ discharge will produce ten times more α -particle energy than generated thus far in the whole history of fusion.

References

[1] Fasoli, A. et al., *Nucl. Fusion* **47**, S264 (2007).
 [2] <http://www.efda.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf>
 [3] Loarte, A. et al., *Nuclear Fusion* **47** (6), S203 (2007).
 [4] Zohm, H., et al., *Nuclear Fusion* **53** (7), 073019 (2013).
 [5] Piras, F. et al., *Plasma Phys. Control. Fusion* **51**, 055009 (2009).
 [6] Villard, L. et al., *Plasma Phys. Control. Fusion* **55**, 074017 (2013).



Courtesy of ITER Organisation

Fig. 5 The ITER construction site in Cadarache, France

François R. Bouchet, Institut d'Astrophysique de Paris, CNRS & Sorbonne Universités-UPMC

This article summarizes a plenary talk which I presented at the joint meeting of the Swiss and the Austrian Physical Societies in September 2015 in Vienna, on behalf of the *Planck* collaboration. In order to make reading easier, I have omitted references. However, the reader may profitably consult the series of 38 papers whose title starts by “Planck 2015 results” (readily found on the arxiv) which updates the 36 papers entitled “Planck 2013 results” (and the 41 papers entitled “Planck Intermediate results” we published in between). Indeed my talk only overviewed some of the main results derived from our measurements of the Cosmic Microwave Background (CMB) anisotropies.



The European Space Agency's *Planck* satellite ¹ is dedicated to studying the early Universe and its subsequent evolution. The satellite was launched on 14 May 2009 and scanned the microwave and submillimetre sky continuously between 12 August 2009 and 23 October 2013. *Planck*'s scientific payload contained an array of 74 detectors in nine frequency bands sensitive to frequencies between 25 and 1000 GHz, which scanned the sky with angular resolution between 33 arcmin and 5 arcmin. The detectors of the Low Frequency Instrument were pseudo-correlation radiometers, covering bands centred at 30, 44, and 70 GHz. The detectors of the High Frequency Instrument – HFI – were bolometers, cooled at 0.1 ± 0.001 K and covering bands centred at 100, 143, 217, 353, 545, and 857 GHz. *Planck* imaged the whole sky twice per year, with a combination of sensitivity, angular resolution, and frequency coverage never before achieved. One should note in particular the excellent sensitivity ² achieved by HFI in the core CMB channels, on which most cosmology results rely, of $1.29, 0.55, 0.78 \mu\text{K}_{\text{CMB}}$ deg at (respectively) 100, 143, and 217 GHz.

¹ *Planck* (<http://www.esa.int/Planck>) is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states and led by Principal Investigators from France and Italy, telescope reflectors provided through a collaboration between ESA and a scientific consortium led and funded by Denmark, and additional contributions from NASA (USA).

² These numbers indicate the *rms* of the fluctuations contributed by detector noise in pixels of 1 degree on a side (leading to 7.5, 4.3, 8.7 μK_{CMB} per (Gaussian) beam solid angle of FWHM equal to 9.66, 7.22, 4.90 arcmin (the *rms* of the CMB anisotropy is about 100 μK_{CMB}). For white noise (a reasonable approximation at scales below a degree), the detector noise scales inversely proportional to the pixel linear size.

The primary product of the mission is therefore a set of nine maps of the sky emission in the 3 LFI and 6 HFI frequency bands, as well as fourteen maps of the Q & U Stokes polarization parameters (the polarization was not measured at 550 and 857 GHz). In order to clean the background CMB map from foreground emissions, we have used four different approaches which combine differently the various frequency maps. Indeed, different methods have different objectives and possibilities, in line with the specific stochastic problem they set out to solve best. Each component separation method produces at least a CMB map, a confidence map (i.e., a mask), an effective beam, and a noise estimate map, together characterizing that CMB map. To help the analyses and validate results, the *Planck* team produced and made available realistic simulations of the *Planck* data set called full focal plane 8 (FFP8). They are based on detailed models of the satellite, instrument and sky. The first 1000 Monte Carlo realizations of CMB and noise have been propagated through the four component separation pipelines.

Aspects of the statistics of the CMB fluctuations were assessed with tests of skewness, kurtosis, multinormality, N-point functions, and Minkowski functionals, and none yielded indications of significant departures from Gaussianity, while the variance of the CMB map was found to be low, in agreement with previous studies. First-order moments of filtered maps also exhibit the low variance anomaly, as well as a kurtosis excess on certain scales associated with the so called "Cold Spot". A study of peak statistics finds results consistent with the expectations for a Gaussian random field, although the Cold Spot is again detected. The low variance anomaly appears to be associated with the known low-l deficit in the angular power spectrum (see below). The lack of large-scale angular correlations, the relatively featureless northern ecliptic hemisphere 3- and 4-point functions, and indications of violations of point- and mirror-parity symmetry are also confirmed (although little attempt was made to correct these for a posteriori effects). Tight constraints on a quadrupolar power modulation were also obtained. Finally, stacking of temperature and polarization peaks was analyzed. They are largely consistent with statistically isotropic simulations, both for oriented and unoriented stacking. The exception is a low unoriented temperature profile, which seems to be yet another reflection of the large-scale power deficit. With the Planck 2015 release, one is probably near the limit of our ability to probe the CMB anomalies with temperature fluctuations alone. The use of large-angular-scale polarization, expected for the final Planck release in 2016, should enable independent tests of these peculiar features. It is a tantalizing possibility that some of the anomalies described so far will take us beyond the standard model of cosmology.

The CMB angular power spectra contain all of the information available if the CMB is statistically isotropic and distributed as a multivariate Gaussian, which we now know is an excellent approximation. For realistic data, these empirical spectra must be augmented with models of instrumental noise, of various instrumental or processing systematic ef-

fects, and of contamination from astrophysical foregrounds. The CMB power spectra are in turn uniquely determined by the underlying cosmological model and its parameters. The CMB is characterized by its intensity (temperature) and its (linear) polarization. Because linear polarization is given by both an amplitude and direction, it can in turn be decomposed into two coordinate-independent quantities with different dependence on the cosmology. One, the so-called E mode which is the curl-free part, is determined by much the same physics as the intensity, and therefore allows an independent measurement of the background cosmology, as well as an improved determination of some parameters. The other polarization observable, the B mode, is only sourced at early times by tensor modes (gravitational radiation), as produced for example during an inflationary epoch. Only E is expected to be correlated with intensity. Thus we expect to be able to measure four independent power spectra, namely the three auto-spectra $C^{TT}(\ell)$, $C^{EE}(\ell)$, $C^{BB}(\ell)$ (unreleased so far) along with the cross-spectrum $C^{TE}(\ell)$.

The analysis of the angular power spectra shown in figure 1 showed that the basic ‘‘LCDM model’’ with only 6 parameters is an excellent fit to the data. These parameters - baryonic and dark matter content, expansion rate, optical depth, amplitude and logarithmic slope, n_s , of the primordial fluctuation spectrum - are measured with per cent level accuracy. The most salient result is $n_s = 0.965 \pm 0.005$ (a hundred-fold improvement in accuracy in the 20 years since the first constraint from COBE/DMR). This at last excludes unity at more than 5σ , therefore establishing a crucial prediction of gener-

ic inflation models reflecting that, if inflation took place and created the fluctuations seeding the latter growth of structures, it had to end. Let me note too that Large scale (low- ℓ) power, with TT versus TE anti-correlation ($5^\circ > \vartheta > 1^\circ$) calls for a period of accelerated expansion to avoid (apparently) a-causal physics.

But negative results are equally important. In particular the *Planck* analysis strictly bounds the amount of primordial Isocurvature fluctuations (whose existence would ruin the polarization prediction of LCDM which is based on curvature fluctuation only), spatial curvature (with $\Omega_k = 0 \pm 5 \cdot 10^{-3}$, a hundred-fold improvement in accuracy in the 15 years since the first constraint from BOOMERANG), the running of the primordial spectra, $dn_s/d\ln k$, as well as the amount of primordial tensor fluctuations of the metric, aka gravitational wave, which is denoted by the tensor to scalar ration, r . *Planck* established $r < 0.11$ at 95%CL, therefore bounding the energy scale of inflation $V_* = (1.6 \times 10^{16} \text{ GeV})^4 (r/0.1)$. As shown in figure 2, the joint constraints on (n_s, r) now exclude models of inflation like the most generic $V_* \propto m^2 \phi^2$. *Planck* also excluded substantial amount of primordial non-gaussianity, which would generically be expected in non-standard/minimal inflationary model (e.g. multi-field inflation, a non-standard kinetic term or higher derivatives in the Lagrangian, non Bunch-Davis pre-inflationary vacuum, etc.). For instance, *Planck* established a constraint on the amplitude on the generic local form of the three-point correlation function, $f_{NL}\text{-Local} = 0.8 \pm 5.0$, a hundred-fold improvement of accuracy in the 14 years since the first constraint from the MAXIMA experiment.

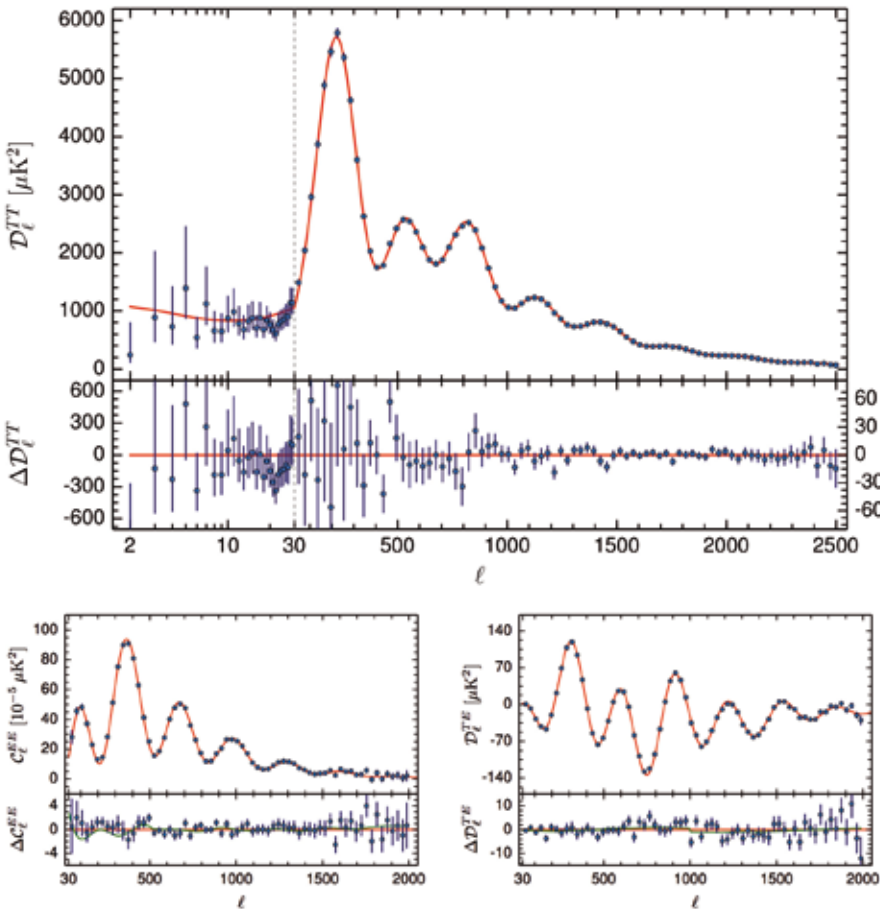


Figure 1: *Planck* 2015 angular power spectra (blue points binned in ℓ) in TT, TE and EE. The best fit LCDM model is shown in red. It is an excellent fit to the data. The residuals w.r.t. this model are shown in the bottom panels. Note that the model parameters are fit using temperature alone, the polarisation spectra being therefore predictions of the model, which also provide an excellent fit to the data.

Planck spectra further set tight constraints on neutrinos properties (e.g. a bound of 0.23 eV at 95%CL on the sum of their masses) and on many potential deviations from the standard model prediction (e.g. on the number of early degrees of freedom of radiation, N_{eff} , the primordial Helium abundance, Y_p , the equation of state of vacuum, w)... It is worth mentioning that the *Planck* data also allowed to properly interpret the BICEP2 result on B-modes and r , by assessing the amount of polarization signal due to dust emission, thereby turning a claimed 5σ detection of primordial gravitational waves into an upper limit of $r < 0.11$ at 95%CL. This thus confirms directly the indirect (and therefore model-dependent) constraint obtained previously by *Planck* which I already mentioned. Another salient result from *Planck* is the large-scale mapping of the lensing potential of large scale structures whose amplitude is now constrained with 2.5% accuracy, providing a 40σ detection of the effect of the projected mass distribution of all the observable Universe.

In summary, cosmological data provide a consistent picture within LCDM. Primordial fluctuations are, to a very good approximation, Isotropic, Gaussian, adiabatic, coher-

ent (fluctuations are laid down at the same time), close to Scale invariant - but not exactly ($n_s = 1$ is excluded at more than 5σ). There are no gravitational waves at the 10 percent level. A flat spatial geometry is a very good approximation. The content, now known with percent accuracy, is rather minimal, i.e. matter is mostly dark (and cold), "Dark energy"

is consistent with Λ ($w = -1$), with a small fraction of baryon (consistent with BBN). The CMB "Anomalies" are present at tantalizing levels, but at large scales. Thus far, this is all consistent within the generic inflationary framework, which completes the Hot Big Bang phase to form the standard model of cosmology.

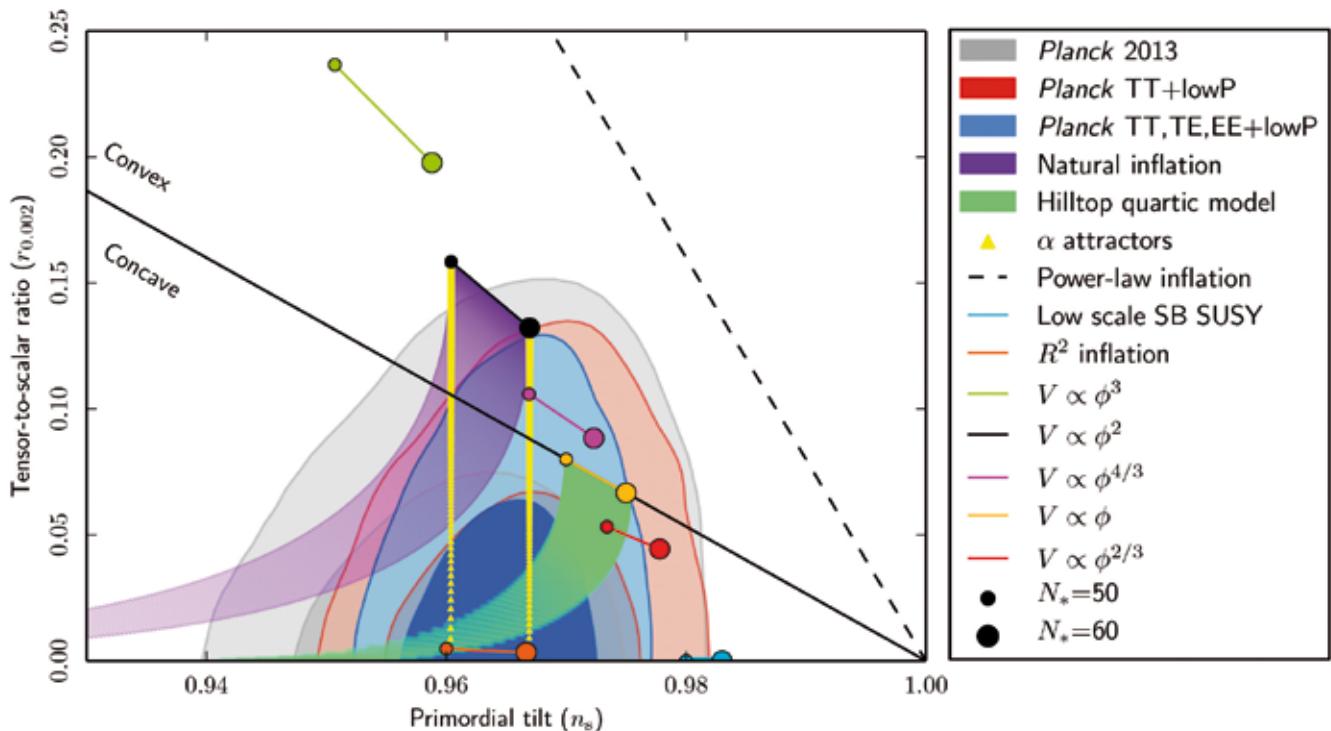


Figure 2: Planck constraints on the inflationary parameters (n_s , r), together with the predictions of a number of models for different number of e -folds N_* .

Kurzmitteilungen - Short Announcements

SATW Transferkolleg: Hochschule und Industrie inspirieren sich gegenseitig

Das SATW Transferkolleg 2016 zum Thema "Functional coatings, layers and interfaces" ist lanciert. Die Schweizerische Akademie der Technischen Wissenschaften (SATW) ruft Fachleute aus Wissenschaft und Industrie dazu auf, innovative Ideen für neue Produkte oder Prozesse zu entwickeln und entsprechende Projektanträge einzureichen. Die besten Ideen erhalten Unterstützung.

Bereits zum zwölften Mal startet die SATW gemeinsam mit der Kommission für Technologie und Innovation (KTI) des Bundes einen Ideenfindungsprozess für Fachleute aus Wis-

senschaft und Industrie. Das so genannte SATW Transferkolleg fördert den Wissensaustausch zwischen Hochschule und Wirtschaft und unterstützt innovative Projekte in einer frühen Phase. In diesem Jahr steht das Transferkolleg unter dem Thema "Functional coatings, layers and interfaces".

Ideen mit Marktpotenzial prämiieren

Beim Transferkolleg arbeiten Forscher aus einer Hochschule oder einer Forschungsinstitution sowie Produktentwickler aus der Industrie zusammen. Sie testen die Umsetzbarkeit

Da der Technologiewandel in Zukunft nicht nur schneller erfolgen, sondern auch zu immer komplexeren Systemen führen wird, müssen Physiker stärker involviert werden. Die Liste der bisherigen Themen (siehe Kasten) lässt eindeutig sowohl die Komplexitätszunahme als auch ihre Wichtigkeit für Schweizer Betriebe erkennen. Nur ohne begleitende physikalische Einsichten wird vieles auf umfangreiche empirische Studien hinauslaufen, die zeit- und kostenintensiv und somit gerade für kleine Unternehmen kontraproduktiv sind.

Als Beispiel seien moderne Materialbearbeitungsprozesse mit Femto-Sekunden-Laser genannt, die, wenn der Laser auf das Material optimal eingestellt wird, als

„kalte“ Prozesse zu hervorragenden Oberflächenqualitäten führen. Diese Einstellparameter werden besonders im asiatischen Raum durch umfangreiche Massentests ermittelt. Hier könnte die Schweiz stark punkten, indem man den Mechanismus erarbeitet, wie Laser und Material aufeinander abgestimmt werden müssen, um der Aufgabenstellung, z.B. den Erhalt einer perfekten Oberflächen-güte, zu genügen. Zur Lösung dieser Ingenieurfragestellung braucht es die Mitwirkung von Experten aus der Festkörper-, Oberflächen- und Kurzzeitphysik.

B. Braunecker

Themen der Transferkollegs

- "Functional coatings, layers and interfaces" (2016)
- "High performance composite materials and industrial production" (2015)
- "Advanced Wood Technologies" (2014)
- "Soft Materials for Advanced Products" (2013)
- "Micro- and Nanotechnologies for Health" (2011)
- "Synthetic Biotechnology" (2010)
- "Food Processing" (2009)
- "Industrial Photonics" (2008)
- "Industrial Biotechnology" (2007)
- "Applied Photonics" (2006)
- "Innovative products with nanostructured surfaces" (2005)
- "Nanotechnology for the Life Sciences" (2004)

einer gemeinsamen Idee für ein neues, marktfähiges Produkt oder einen verbesserten Prozess. Akzeptierte Projektideen erhalten nach einem unbürokratischen Auswahlprozess einen Unterstützungsbeitrag von 16'000 Schweizer Franken. Mit diesem Beitrag können die Projektpartner erste, wichtige Machbarkeitstests durchführen. An einem Workshop evaluieren sie unter der Leitung ausgewiesener Innovationsspezialisten die Zukunftschancen ihrer Projektidee und erarbeiten geeignete Massnahmen für die Weiterführung. Der Austausch mit den anderen Projektteams erlaubt es zudem, von der Expertise der anderen zu profitieren, den eigenen Horizont und das Netzwerk zu erweitern.

Transferkolleg 2016 zum Thema "Functional coatings, layers and interfaces"

Neue, funktionelle Oberflächen sind in vielen Bereichen unentbehrlich geworden, denn sie ermöglichen neue Produkte und schaffen Wettbewerbsvorteile. Da viele der neuen Technologien Fachwissen entlang der Wertschöpfungskette verlangen, ist eine frühe Zusammenarbeit zwischen Hochschulen und der Industrie für eine schnelle Umsetzung unentbehrlich. Das diesjährige Transferkolleg wird dazu beitragen, solche Teams bei der Identifizierung neuer Chancen und deren technischer Umsetzung zu unterstützen. Projektideen aus folgenden Gebieten sind willkommen:

- Schichten und Grenzflächen mit verbesserter Qualität, Lebensdauer, Härte, mechanischer oder chemischer Widerstandskraft.
- Oberflächen, die in Kontakt sind mit biologischen Materialien und welche spezielle Eigenschaften aufweisen wie Biokompatibilität, Bioabbaubarkeit, antimikrobielle Eigenschaften, verbesserte Hygiene, langsame Freisetzung von Wirkstoffen, Katalyse oder Reaktionsinhibition.
- Funktionale Oberflächen für Sensoren, Aktoren, Energiegewinnung oder Speicherung.

www.satw.ch/transferkolleg

Esther Koller-Meier, Marc Pauchard und Werner Rutsch

SATW INFO "Das Potenzial von Augmented Reality für die Bildung"

Augmented Reality bezeichnet die computergestützte Erweiterung der Realitätswahrnehmung, abgeleitet von «Augmentation» für "Steigerung" und "Zuwachs". Augmented Reality (AR) kann Unsichtbares sichtbar machen: Veränderungen eines Gebäudes im Laufe der Jahrhunderte, die künftige Entwicklung eines Stadtquartiers, die Entstehungsgeschichte eines Kunstwerks.

Im September 2014 trafen sich Fachleute unterschiedlicher Fachbereiche wie Pädagogik, Technik, Kunst, Design und Kulturwissenschaften zu einem SATW-Workshop, um Nutzen und Herausforderungen von Augmented Reality für die Bildung herauszuarbeiten. Als Resultat des Workshops ist eine SATW INFO entstanden. Diese informiert darüber, was unter Augmented Reality zu verstehen ist, welche Rolle die Technologie in der schulischen und musealen Vermittlungstätigkeit einnehmen kann, und stellt schliesslich konkrete Umsetzungen aus dem Schul- und Museumsbereich vor, die in der Schweiz realisiert wurden.

Die SATW INFO handelt aber nicht nur von Augmented Reality, sondern ist selbst Augmented Reality, denn die Bilder sind «augmentiert». Um die Augmentierung zu erleben, benötigen Sie die kostenlose App Layar. Einfach die App über den App Store oder Google Play herunterladen, mit der App die Bilder scannen und schon beginnt die Reise in die Augmented Reality. Viel Vergnügen!

Link auf SATW INFO: http://www.satw.ch/publikationen/SATW-INFO_3-15_AR_DE.pdf

SATW INFO «Le potentiel de la réalité augmentée pour la formation»

Le terme «réalité augmentée» désigne une extension de la perception du réel assistée par ordinateur. La réalité augmentée permet de rendre visible ce qui ne l'est pas: l'évolution d'un bâtiment au fil des siècles, le développement futur du quartier d'une ville, l'historique d'une œuvre d'art.

En septembre 2014, des spécialistes issus de différentes disciplines (pédagogie, sciences techniques, art, design et études culturelles) se sont réunis à l'occasion d'un atelier SATW afin de discuter des bénéfices et des défis que présente la réalité augmentée pour le domaine de l'éducation. L'atelier a donné lieu à la publication d'un numéro de SATW INFO. Celui-ci explique la notion de réalité augmentée, décrit le rôle que peut jouer cette technologie dans les activités de médiation scolaire et culturelle, et présente enfin des exemples concrets réalisés dans des écoles et des musées en Suisse.

Mais ce numéro de SATW INFO ne fait pas que traiter de réalité augmentée, il en est lui-même un exemple, car ses images sont «augmentées». Afin de vivre cette expérience, vous aurez besoin de l'application gratuite Layar. Téléchargez simplement l'application via l'App Store ou Google Play, scannez les images avec l'application, et vous voilà partis pour un voyage dans la réalité augmentée. Nous vous souhaitons beaucoup de plaisir!

Lien vers SATW INFO: http://www.satw.ch/publikationen/SATW-INFO_3-15_AR_FR.pdf

History of Physics (15)

Born's outstanding role in the formulation of Quantum Mechanics

Jan Lacki, History and Philosophy of Science, University of Geneva

Max Born received the Nobel prize in physics for the year 1954 sharing this distinction with Walter Bothe. He was awarded the prize "for his fundamental research in quantum mechanics, especially for his statistical interpretation of the wavefunction".

The Nobel prize for Born, the year following his retirement, came, in the opinion of many, rather late ¹. After all, most of the heroes in the development of quantum mechanics were since long laureates (Bohr, Dirac, Schrödinger, Pauli) even if some other characters remained unjustly discarded (to quote but one, Sommerfeld, many times nominated but never awarded). This is not to say that Born deserved the Nobel more than some of his predecessors. Nobel prize politics reflect delicate issues of balance (fields considered, nationalities, etc.) so that purely scientific reasons are not solely decisive. Also, we are today used to Nobel prizes awarded decades after the decisive contribution actually happened (for instance the awards granted to Jack Steinberger or Albert Fert, just to take this two). From this perspective, Born being awarded the prize some thirty years after he proposed his statistical interpretation and obtained his best results hardly leaves matter for criticism. Still, given Born's numerous contributions to 20th century physics, some of them fundamental, an earlier distinction would have been highly deserved. This paper is an attempt to bring some fuel to this statement; although it will focus on Born's contributions to general problems in the foundations of quantum mechanics, one should not forget Born's considerable achievements in the quantum theory of solids, in optics, and non-linear electrodynamics ².

Life and scientific career

Max Born was born in Breslau (present time Wrocław on Polish territory) in 1882, son of Gustav Born, professor of anatomy and Margarethe Kauffmann from a family of Silesian industrialists. After his gymnasium curriculum he entered Breslau university in 1901. After some semesters and the decision to turn to the study of mathematics and exact sciences, Born continued his studies in Heidelberg and then Zurich, to finally enroll the university of Göttingen in 1904. Soon (1905) he became Hilbert's private assistant in charge of preparing the transcripts of the master for the mathematics reading room and this should be traced back as the main origin of his mathematical skills. On the other hand, Born has at the time also been influenced by the teaching of Hermann Minkowski who, following his recent physics interests, was

running a seminar on the electron theory where results of prominent contributors to electrodynamics, and then especially Lorentz, Poincaré and of course Minkowski, were discussed. Although Born's interest was definitely in electron theory and soon relativity, a clash with the almighty Felix Klein constrained him to consider for his dissertation topic elasticity theory where Born showed great competence as well. After completing his Ph.D. in 1907, Born returned to Breslau only to come back to Göttingen in 1908 following an invitation from Minkowski to become associate. The untimely death of Minkowski put an end to a promising collaboration and saw Born, still regarded with animosity by Klein, find some support from Hilbert and Runge, which enabled him to obtain his habilitation under the guidance of Wolde-mar Voigt. In 1909 Born visited for a couple of months J. J. Thomson and J. Larmor in Cambridge to learn more electron physics and then returned to Breslau where he could have a better look at Einstein's theory which deeply impressed him. At the time Born was mainly active in relativity but from 1912 on, he started as well his life long interest in the physics of crystal lattices, again inspired by seminal papers of Einstein on specific heats. He obtained, among others, in collaboration with von Karman results which would be independently exposed by Debye. Born's academic career followed in 1915 with a call from the University of Berlin to become extraordinary professor assisting Max Planck. In spite of the difficult time of war, Born could spend there some of his best years, keeping close to Planck and especially Einstein with whom he developed a life long friendship. After a teaching position in Frankfurt where he replaced von Laue, Born was offered a position in Göttingen where he came back to strengthen the local faculty, making its university one of the most prominent scientific places in Germany. Although still working on lattice theory, Born soon fell under the spell of quantum theory, especially after memorable lectures that Niels Bohr gave there in 1921. This marks the most well known period of Born's career as quantum physicist. His many successes did not protect Born from enduring hardship, as many other Jewish civil servants, when Nazis came to power. In April 1933 he was placed on "leave of absence" and left Germany in following May. Thanks to the intervention of Patrick Blackett, Born could obtain a modest position as lecturer in Cambridge until, in 1936, he succeeded Charles Darwin on the Tait chair of natural philosophy in Edinburgh where he reconstructed a research group matching his expertise. He retired in 1953 and returned to Germany the following year. He died there in 1970.

Born's contributions to the "old quantum theory"

The year 1926 saw the remarkable unification of matrix and wave mechanics culminating in the transformation theory of Dirac, Jordan and London. John von Neumann in turn gave transformation theory its ultimate mathematical edge in terms of a mathematical theory that he created for this purpose: Hilbert space theory and the associated theory

¹ It was not for lack of nominations. For instance, Einstein proposed him, together with Heisenberg and Jordan, in 1928. Out of the three, only Heisenberg obtained the prize for year 1932. Being distinguished alone caused moral discomfort to Heisenberg: it is well known that in a letter to Born, he expressed his "bad conscience" that he alone had received the Prize "for work done in Göttingen in collaboration — you, Jordan and I". For details, see [GREENSPAN 2005] and [SINGH AND RIESS 2013].

² The present paper follows a previous one by Emil Wolf in issue 47 of the *SPG Mitteilungen* where Born and his science is being recollected on a more personal basis. This mini-series devoted to Born will end with an account of some aspects of Born's mathematical physics in the next issue..

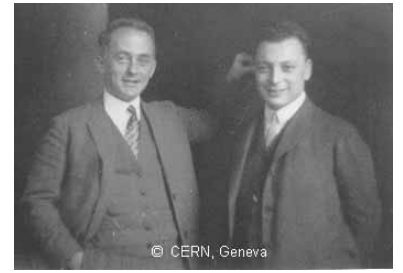
of unbounded self-adjoint operators. However, when trying to come to terms with atomic physics before the advent of quantum mechanics, physicists were not completely helpless. There existed, in the decade following Bohr's theory of the Hydrogen atom (1913), a fairly sophisticated semi-classical theory of atomic phenomena which transposed to atomic physics the theoretical framework of celestial mechanics developed in 19th century. Historians often dub this theory the "old" quantum theory. Its key idea was to approximate atoms as multiply periodic systems where, introducing action-angle variables, one could express the time evolution of any physical quantity $O(t)$ pertaining to the system as a multiple Fourier series expansion of the form

$$O(\hat{t}) = \sum_{n_1, n_2, \dots, n_g = -\infty}^{\infty} O_{n_1, n_2, \dots, n_g}(J_1, J_2, \dots, J_g) \cdot \exp(2\pi i(\nu_1 n_1 + \nu_2 n_2 + \dots + \nu_g n_g) \hat{t}).$$

In the expression above, the coefficients O_{n_1, n_2, \dots, n_g} of the expansion, indexed by integers n_i , depend solely on the action variables J_i which are quantized following the "Bohr-Sommerfeld rules", namely $J_i = \tau_i h$, with τ_i the quantum numbers characterizing the orbit (stationary state) considered. The oscillating terms $\exp(2\pi i(\nu_1 n_1 + \nu_2 n_2 + \dots + \nu_g n_g) \hat{t})$ depend on phases which involve linear combinations of classical frequencies ν_i which characterize the periodic motions underlying the system's dynamics. The number of the action variables, g , corresponds usually to the number of degrees of freedom but, in degenerate cases, it can be less. In what concerns the quantum meaning of such expressions, the harmonic terms were interpreted, following Bohr's "correspondence principle", in terms of transitions between the stationary states of the quantum system. More precisely, quantum physicists were reinterpreting such series in terms of quantum jumps between orbits corresponding to quantum numbers τ_i and $\tau_i + n_i$, the square of the modulus of the expansion coefficient $|O_n(J_i = \tau_i h)|^2$ providing information on the relative frequency of such jumps and hence on the intensity of the corresponding spectral lines³.

Born's interest in quantum theory was ultimately triggered by the famous series of lectures Niels Bohr delivered in Göttingen in 1921 (the so-called Bohr *Festspiel*) explaining the state of the art in atomic physics. This was a topic where Born could perfectly invest his considerable expertise in mathematical physics and broaden his interest in quantum physics up to then focussed, following Einstein's work, on the consequences of Planck's quanta on the theory of solids. Born contributed to the old quantum theory in several papers which were showing how to apply perturbation theory to tackle the problems of complex atoms and complex spectra, which could not be directly described as multiply periodic systems (for instance his papers with Brody [BORN AND BRODY 1921], or with Pauli [BORN AND PAULI 1922]). Interestingly enough, Born was at the time also focussing his research on attempts to obtain, following Bohr's correspondence principle, systematic translations of (classical) differential operators in terms of (finite) difference operators taking into account the discrete spectrum of Bohr's stationary

states. As the difference expressions obtained could be considered, in a sense, as genuine quantum ones, one of Born's papers is significantly entitled *Über Quantenmechanik*, published in 1924. Soon later Born and his student Jordan used the translation technique in a paper *Zur Quantenmechanik aperiodischer Vorgänge*, which considered again Planck's foundational case of resonators in a radiation field. What they found was that quantum physics was in an essential way involving pairs of states and associated "transition amplitudes". The importance of these developments becomes clear when one realizes that all this was happening just months before Heisenberg's breakthrough in summer 1925.



Max Born and Wolfgang Pauli
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Born and quantum mechanics

As is well known, the birth of quantum mechanics took place with a seminal paper of Werner Heisenberg in 1925 [HEISENBERG 1925]⁴. This was to start the first formulation of quantum mechanics in his "matrix mechanics" disguise. Without entering details, Heisenberg, an expert in the field of the old quantum theory, concentrated on the formal manipulations one could perform on the Fourier series associated to multiply periodic systems recognizing that their physical content was (solely) contained in the expansion coefficients (intensities and frequencies of spectral lines) rather than in the series as such which, when summed, would point to unobservable quantities such as the trajectories of the electron. Focussing then on such sets of coefficients $\{O_n(\tau h)\}_{n=-\infty}^{\infty}$ as tentative new mathematical representatives of physical observables (for ease of exposition, I consider the case of a single degree of freedom), Heisenberg tried to guess the logic of the algebraic manipulations that one could fancy between them. For instance, knowing that a physical quantity O is associated to the set $\{O_n(\tau h)\}_{n=-\infty}^{\infty}$, what would be the set associated to the square quantity O^2 ? The parenthood with Born's *Quantenmechanik* program should at this point be obvious. Showing impressive intuition and cleverness, Heisenberg obtained the rules for "multiplication" which enabled him to write down the first genuinely quantum equations, which he successfully tested in the cases of the harmonic and anharmonic oscillator. However, his new algebraic rules, that he discovered with embarrassment to be non-commutative, remained in his paper mathematically uninterpreted. This is where Born entered (again) the scene.

Heisenberg obtained his breakthrough while he was trying to get some relief from a severe attack of hay fever on the island of Helgoland on the North Sea facing Hamburg. Serving at the time as Born assistant and preparing with him his habilitation, he sent Born a draft of his paper in July 1925. Born soon recognized that the odd rules of Heisenberg were in fact corresponding to matrix multiplication, i.e. Heisenberg's sets $\{O_n(\tau h)\}_{n=-\infty}^{\infty}$ were to be viewed as two dimensional (infinite) arrays of complex numbers with matrix algebra rules. At the time, matrices and matrix algebra

³ Bohr's "correspondence principle" is a tricky piece of physical intuition which shows how physicists following Bohr were getting their way out of the maze of quantum facts. It is fairly remote from what we understand today under the same designation, namely sending Planck's constant to zero and (roughly speaking), recover classical physics. For the details of what it meant in the twenties, see [JAMMER 1966], p. 102-118, and [HUND 1967].

⁴ For a general history, see [JAMMER 1966], [MEHRA AND RECHENBERG 1982, 1987].

were rather exotic mathematics even among mathematicians. This deserves clarification: of course, the mathematical situations where today we immediately identify the need for "matrix thinking" (typically the solving of systems of linear equations, etc.) were mathematical commonplace since centuries, but their interpretation in terms of what we call today linear algebra was rather rare. Vector spaces and the thinking in terms of "intrinsic" objects (vectors, linear mappings, etc.) was not yet widespread. Born recognizing that Heisenberg was actually handling matrices illustrates then his remarkable mathematical culture and acuity.

But Born did not stop there. Jumping in the train started by Heisenberg, Born immediately proposed Pauli to work on an extensive and systematic formulation of Heisenberg's proposal in terms of matrix algebra. Ironically, Pauli, who was not (yet) fond of mathematical sophistication, turned Born's proposal down, so the latter turned next to his more mathematically minded assistant Jordan ⁵. They published a first paper entitled *Zur Quantenmechanik* [BORN AND JORDAN 1925] where the authors could, among others, prove the consistency of the odd non-commutative rules hinted at by Heisenberg. In the sequel, *Zur Quantenmechanik II*, authored together with Heisenberg who was back from Copenhagen where he was visiting Bohr, a full fledged theory of matrix mechanics was released [BORN, HEISENBERG AND JORDAN 1926], marking the beginning of quantum mechanics. Here is a brief summary of this remarkable paper.

In the case of a multiply periodic system, to each quantum theoretical quantity A one associates the set of numbers $a(nm) \exp(2\pi i n (nm) t)$ ⁶. These coefficients are understood as defining a matrix \mathbf{a} . The usual matrix operation rules are assumed to hold. The fundamental relation between canonical matrices,

$$\mathbf{p}\mathbf{q} - \mathbf{q}\mathbf{p} = -i\hbar\mathbf{1} \quad (1)$$

enables to calculate products of quantum theoretical quantities. Given a Hamiltonian matrix \mathbf{H} , the relations (1) ensure the validity of the canonical equations ⁷

$$\dot{\mathbf{p}} = -\frac{\partial \mathbf{H}}{\partial \mathbf{q}}; \quad \dot{\mathbf{q}} = \frac{\partial \mathbf{H}}{\partial \mathbf{p}}$$

which account for the dynamics of the system. Bohr frequency conditions

$$h\nu(nm) = H_n - H_m$$

⁵ Indeed, Pauli was suspicious of sheer mathematical virtuosity (of which he considered Born a distinguished representative) and tended in these years to favor most physical intuition. He was for instance the one who insisted that his slightly younger colleague and friend Heisenberg should, after his Göttingen experience, go to Copenhagen to "learn physics from Bohr". Jordan had, on the contrary, no such second thoughts about mathematics. He was at the time also involved with Hilbert and the editorial project of lecture notes that the latter was carrying on with Courant, the well known *Methods of Mathematical Physics*.

⁶ The typically integer indices n, m label the (discrete) set of stationary states of the system. The frequencies $\nu(nm)$ are characteristic of the transitions between state n and m which becomes manifest in the Bohr frequency conditions below. The origin of such expressions goes back to the use of multiple Fourier expansions of the old quantum theory, see above.

⁷ \mathbf{H} is assumed to be a function of the (matrices) \mathbf{p} and \mathbf{q} . The explicit form of the latter depends on the problem considered and is usually inherited from the classical expression.

for the transition frequencies $\nu(nm)$ of quantum jumps between stationary states recovered when the Hamiltonian matrix is diagonal, with H_n its n -th diagonal element corresponding to the energy of the n -th stationary state, and h Planck's constant. The dynamical problem amounts thus to finding a set of matrices obeying (1) such that the corresponding Hamiltonian expressed in terms of the latter is diagonal. The main tool for diagonalization are the (canonical) transformations

$$\mathbf{H} \rightarrow \mathbf{S}^{-1}\mathbf{H}\mathbf{S} \quad (2)$$

Born, Heisenberg and Jordan developed in their paper the stationary and time dependent perturbation theories, obtaining perturbative expansions for the diagonalization matrix \mathbf{S} . In this case the latter has an expansion of the form $\mathbf{S} = \mathbf{1} + \mathcal{O}(\epsilon)$ where ϵ is a small parameter, so that the computation of \mathbf{S}^{-1} can be formally handled.

A contemporary reader will immediately recognize in Born's and collaborators' formalism what we call today the "Heisenberg representation" of quantum dynamics, where time evolution is carried solely by observables. At the time, the situation was even more radical since states were just absent from matrix mechanics ⁸. This is simple to understand. Although the fathers of matrix mechanics used matrices to express the formalism, they did not associate to them any "mapping" meaning. The matrices were thought as pure arrays of numbers deprived of any operatorial meaning. The latter came only with transformation theory roughly a year later, prompted by the need to understand the equivalence of matrix mechanics with Schrödinger wave-mechanics where states are explicit (the wave functions).

Another shortcoming of the original approach of Born and his collaborators was that it seems to make sense only in the case of a discrete spectrum of stationary states. Only then it is possible to deal with the matrices without the ill-defined Dirac δ -function ⁹. This is indeed the case in multiply periodic systems exhausting the models of Bohr's atomic theory (discarding the continuous portion of the spectrum), but not in scattering processes and other non-periodic phenomena.

Born and Wiener almost discovered wave-mechanics

Starting with the foundational paper of Born, Jordan and Heisenberg, progress was moving in an increasingly fast pace. Studying Heisenberg's paper and without contact with the Germans, Dirac recovered and extended independently Heisenberg's original ideas in terms of a calculus of abstract non-commuting "q-numbers" in a series of papers which marked his entering the quantum scene [DIRAC 1925, 1926AB]. Then, only a couple of months later, Erwin Schrödinger introduced in a series of four papers the differential equations of wave mechanics [SCHRÖDINGER 1926ABCD] ¹⁰. In the first months of 1926, quantum mechanics was then expressed in three

⁸ Of course, matrix mechanics considers stationary states, as it inherits many of its concepts from the old quantum theory, but I am meaning here the genuine quantum states as they are considered in present day quantum mechanics (i.e. elements in a Hilbert space).

⁹ Even if one was ready to consider "matrices" with continuous ranges of indices, one had to face singularities on the diagonal.

¹⁰ I refrain from quoting the basic elements of Schrödinger's wave mechanics as they are, up to subtle interpretation differences, very much what is taught today.

very different formulations (if we dissociate Dirac's one from matrix mechanics, since Dirac's q-numbers are more general and need not be realized as matrices).

Actually, there was even a fourth formulation, forgotten today, an operator calculus due to Born and Wiener. To circumvent the shortcoming of the restriction to only purely discrete spectra (see above) which technically prevented matrix mechanics from describing even such simple situations as free motion (its Hamiltonian has obviously continuous spectrum), Born and Norbert Wiener ¹¹ used the opportunity of Born's series of lectures at the MIT Massachusetts in winter 1925-1926, to collaborate and submitted in January 1926 a joint paper *Eine neue Formulierung der Quantengesetze für periodische und nichtperiodische Vorgänge*. It was exposing a new formalism using as fundamental formal devices linear operators [BORN AND WIENER 1926]. This was done in the following way. A matrix with coefficients $q(mn)$ is associated with a linear transformation acting on "vectors" with coefficients x_n

$$y_m \equiv \sum_n q(mn) x_n$$

which, in case one defines the function $x(t)$ with the help of the Fourier series

$$x(t) = \sum x_n \exp\left(\frac{i}{\hbar} W_n t\right)$$

yields the functional transformation

$$y(t) = \sum y_m \exp\left(\frac{i}{\hbar} W_m t\right) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T q(t, s) x(s) ds \quad (3)$$

with kernel $q(t, s)$

$$q(t, s) = \sum_{mn} q(mn) \exp\left(\frac{i}{\hbar} (W_m t - W_n s)\right).$$

The linear operator q is then formally defined as

$$q = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T ds q(t, s) \dots$$

It transforms a given function $x(t)$ into another one $y(t)$. One may reciprocally associate with each operator a matrix going backwards the steps above. Using this framework, Born and Wiener reformulated matrix mechanics replacing systematically all the matrices by their operators and applied the new approach to the simplest non-periodic system, free motion. As we see, Born and Wiener operators are basically the operators of "our" quantum mechanics and the vectors are the wave functions if we think them expressed in the basis of energy eigenstates ¹². Indeed, and this belongs to the long list of lost opportunities in history of science, when Born and Wiener explained to Hilbert their approach, the latter suggested them to have a look at his theory of inte-

gral equations which, a posteriori, exposes just the mathematics needed to reach, from Born and Wiener proposal, wave mechanics. His advice was not followed or maybe not sufficiently enough: be it as it may, Born and Wiener missed the opportunity to discover wave mechanics before Schrödinger, in the sense that they could have written the evolution (Schrödinger) equation before Schrödinger published his own results ¹³. One should however remark that the starting point of Schrödinger was quite different, being essentially motivated by de Broglie's particle-wave duality for matter and the classical Hamilton-Jacoby theory.

Born's statistical interpretation

In order to understand the origin of Born's interpretation of the square modulus of the wave function, one has to recall what was known of quantum theory in the middle of 1926. As soon as Schrödinger exposed his wave mechanics, there was the need to understand the relation of his formalism with matrix mechanics. The first "proof" of equivalence was given by Schrödinger himself [SCHRÖDINGER 1926E] as an immediate sequel to his foundational papers. For each pair of (normalized) eigenfunctions, say ψ_n and ψ_m , and a physical quantity $A(p_k, q_k)$, Schrödinger showed that the expressions

$$A_{nm} = \int dq \psi_n A\left(-i\hbar \frac{\partial}{\partial q_k}, q_k\right) \psi_m$$

yielded the coefficients of the corresponding Heisenberg matrix ¹⁴. He insisted (much) less on the opposite, that one could derive his wave solutions knowing Heisenberg's ones ¹⁵. In his early paper *Quantum Mechanics and a Preliminary Investigation of the Hydrogen Atom* ([DIRAC 1926A], submitted January 22), Dirac, studying the quantum analogue of action-angle variables, introduced the fundamental interchange relations

$$e^{i(\alpha q)} f(q, p_r) = f(q_r, p_r - \alpha_r \hbar), \quad (4)$$

$$f(q_r, p_r) e^{i(\alpha q)} = e^{i(\alpha q)} f(q_r, p_r + \alpha_r \hbar),$$

$$\text{with } (\alpha q) \equiv \sum_{r=1}^f \alpha_r q_r, \quad (5)$$

where the index r runs over the f degrees of freedom. This enabled him to deal with the quantum analogues of the classical multiply periodic expansions of the form

$$x = \sum_{\alpha} x_{\alpha}(J_r) e^{i(\alpha w)}$$

Commuting the x_{α} across the $e^{i(\alpha w)}$, and using the canonical commutation relations, Dirac could obtain q-number formulas displaying the same structural features as the ones of matrix mechanics. This was, in Dirac's terms, a proof of the possibility of representing his q-numbers by Heisenberg's matrices made out of c-numbers. He would later talk of a given "matrix scheme". Dirac studied later this correspond-

¹¹ Born and Wiener were acquainted since Wiener's sejour in Göttingen in summer 1925.

¹² Pauli, when trying to understand the equivalence between matrix and wave mechanics, introduced operators as well, but in a form different from that of Born and Wiener, see [MEHRA AND RECHENBERG 1987], chap. IV. The operator approach was used also by others in their attempts to prove the equivalence of matrix and wave mechanics; among others, C. Eckart [ECKART 1926AB]. Actually, Cornelius Lanczos proposed as early as end of 1925 a systematic way of obtaining continuous equations equivalent to matrix ones using integral equations and the formalism of Green functions [LANCZOS 1926], but did not provide any new application.

¹³ Born recognized this years later, see [MEHRA AND RECHENBERG 1982], vol. 3, p. 244.

¹⁴ Although Schrödinger realized that to some extent the quantity $\psi\psi^* = |\psi|^2$ played the role of a weight function in the configuration space (this interpretation can be found in [SCHRÖDINGER 1926D], pp.109-139), the full probabilistic meaning of $|\psi|^2$ came only with Born's statistical interpretation.

¹⁵ As soon as Schrödinger published his theory, a rivalry started between matrix and wave mechanics, each formalism claiming true description of quantum physics, quantum jumps against wave nature of matter.

ence in a more general setting acting directly with q-numbers on Schrödinger's eigenfunctions [DIRAC 1926B]. In spite of these correspondences between the various approaches, there was a definite lack of understanding of which were just the essential structural features underlying new quantum mechanics. The answer to this question implied to identify the common structure behind its different and sometimes restricted realizations which were understood as mutually equivalent only as far as all related to the original matrix formulation and, of course, all were providing same physical results. This is where Born made again a decisive contribution.

Born's interpretation emerged out of his interest, since the very first moments, to reformulate the theory in order to be able to handle non periodic situations where the spectra had continuous parts. His operator theory developed together with Wiener was explicitly within this program. It is remarkable that Born's persistence in dealing with the problem eventually made him hit on the statistical interpretation. It was mentioned for the first time in a preliminary notice ([BORN 1926A], submitted June 25), and then made more explicit in Born's subsequent paper ([BORN 1926B], submitted July 21) devoted to the study of scattering off a potential, *Quantenmechanik der Stossvorgänge*. Born's introduction to his paper is illuminating. He first reminds the reader of the conflicting views on atomic events carried by the two quantum formalisms of his time: on one side matrix mechanics, with its underlying claim of the impossibility of a unified description of events in space and time (hence quantum jumps) and the introduction of an alternate account in terms of (solely observable) intensities and frequencies of spectral lines, and on the other side wave mechanics, supposing instead a fundamental wave-like nature of matter. None is, to Born's opinion, totally satisfying. He proposes to derive then a third interpretation. His guiding line is Einstein's understanding of the relation between light quanta and the corresponding wave field. Waves, kind of "Gespensterfeld", determine the probability for the quanta to follow a given path. Only quanta carry energy and momentum, the field does not. By analogy, Born proposes then to think of the Schrödinger waves as "Gespensterfeld" or better, as he writes, "Führungsfeld" for electrons. The Schrödinger "Führungsfeld" propagates causally following Schrödinger's equation. Electrons carry energy and momentum and their trajectories are determined only by the requirements of conservation principles and by the probabilities following from the Schrödinger's field. In Born's words:

The motions of particles follow probability rules, but the probability itself propagates in accordance with the causal principle ¹⁶.

But how to test this view? Periodic processes are unsuitable to probe this hypothesis ¹⁷. One should then consider as the next case non-periodic but stationary processes, and this is why Born considers in the sequel the case of scattering off a time-constant potential (the even more demanding case of non-periodic and non-stationary motion is only alluded to). This is then the context where Born proposes his

famous approximation scheme to general scattering problems known today as Born's approximation. Leaving aside the details of his approach (trained physicists know them well), I want to concentrate instead on Born's statistical interpretation alluded to in his introduction. Born reminds us first that in the case of periodic events where the stationary Schrödinger equation has as solutions the set of eigenfunctions ψ_n , a superposition of such solutions:

$$\psi = \sum c_n \psi_n \quad (6)$$

begs for an interpretation where the square moduli $|c_n|^2$ provide the probability for the system to be in the state n . Going to the continuous spectrum case (free motion is considered) and using the Fourier expansion

$$\psi(x) = \frac{1}{2\pi} \int c(k) e^{ikx} dk ,$$

Born interprets again $|c(k)|^2$ as the relative frequency of states in the interval $(2\pi)^{-1} dk$ centered at k . One will however not find in Born's paper explicitly the emblematic statement that $|\psi(x)|^2$ yields a density of probability for location. Within Born's logic at that time, this would have required to consider an improper expansion of the type

$$\psi(x) = \int \psi(y) \delta(x-y) dy ,$$

which he did not. This is certainly related to the fact that Born did not really grant (6) the meaning of a representative of a (quantum) state. It was then for him rather something expressing a situation of statistical mixture ¹⁸. We encounter here again the oddity of how the various schemes of quantum mechanics in the period immediately preceding transformation theory were then understood: to say it again, the linear features of the mathematical reality underlying the various formulations, and their consequences in terms of physical interpretation were yet unclear.

To show the importance of Born's interpretation for the general development of the theory (going beyond their practical use in computing probability distributions), let me discuss two achievements that missed, or, on the contrary, drew full consequences from Born's proposal.

To start with, let's consider the remarkable contribution of Fritz London to transformation theory. In a paper [LONDON 1926B] more or less contemporary to Born's, he was the first to recognize (months before Dirac and Jordan, which is, given the blazing pace of event at the time, substantially earlier) that the basic mathematical ingredient of what underlied matrix and wave mechanics was the use of infinite dimensional spaces where, so to speak, "Heisenberg matrices act on Schrödinger's functions". He came thus very close to transformation theory but his picture still missed a crucial element: ignoring Born's interpretation which was just starting to spread out, London did not associate any

¹⁸ This is clear in his paper *Das Adiabatenprinzip in der Quantenmechanik* ([BORN 1926C], pp. 168-169). It is possible that Born was still under the "spell" of the same problem that prevented him from "inventing" the concept of quantum state in his and Wiener's operator formalism which we mentioned above. At closer inspection, the abstract column vectors on which act the Born-Wiener operators are, in their formalism, mere dummy arguments. Born-Wiener did not bother asking the question of the possible meaning of these dummy vector variables, and of their possible counterparts in the conventional matrix mechanics.

¹⁶ [BORN 1926B], p. 804.

¹⁷ Such processes, proper, do not propagate in time.

physical meaning to the wave function itself¹⁹. Jordan and Dirac in their respective versions of transformation theory, this time knowing well Born's proposal, instead fully included it in their constructions²⁰.

Another proof of the importance of Born's proposal for the general development and understanding of the theory is Pauli's generalization of the statistical interpretation to other quantities obtainable from the wave function. Usually, this generalization is traced back to a note in Pauli's paper *Über Gasentartung und Paramagnetismus* ([PAULI 1927], p. 83). The reader is nowadays better served looking at a 1926 letter from Pauli to Heisenberg where the whole matter is discussed in a more elaborated form²¹. Pauli extends there first Born's interpretation to the squared modulus of the wave function in momentum space and then considers even more general possibilities. Let me quote him extensively, p. 347:

[...] wieso denn die genannten Matricelemente dazu kommen, die Stoßwahrscheinlichkeiten zu bestimmen. Die Richtung, in der man da steuern muß, ist glaube ich, folgende. Die historische Entwicklung hat es mit sich gebracht, daß die Verknüpfung der Matricelemente mit der Beobachtung zugänglichen Daten auf dem Umweg über die emittierte Strahlung vorgenommen wird. Ich bin aber jetzt mit der ganzen Inbrunst meines Herzens davon überzeugt, daß *die Matricelemente mit prinzipiell beobachtbaren kinematischen (vielleicht statistischen) Daten der betreffenden Teilchen in den stationären Zuständen verknüpft sein müssen*. Ganz abgesehen davon, ob überhaupt und was (elektromagnetisch) gestrahlt wird (Lichtgeschwindigkeit \propto gesetzt). Auch zweifle ich nicht, daß dahinter der Schlüssel zur Behandlung der unperiodischen Bewegungen verborgen ist. - Nun ist es so: alle *Diagonalelemente* der Matrizen (wenigstens von Funktionen der p allein oder der q allein) kann man überhaupt schon jetzt kinematisch deuten. Denn man kann ja zunächst nach der Wahrscheinlichkeit fragen, daß in einem bestimmten stationären Zustand des Systems die Koordinaten q_k seiner Teilchen ($k = 1, \dots, f$) zwischen q_k und $q_k + dq_k$ liegen. Die Antwort hierauf ist

$$|\psi(q_1 \dots q_f)|^2 dq_1 \dots dq_f ,$$

wenn ψ die Schrödingersche Eigenfunktion ist. (Vom *korpuskularen* Standpunkt aus ist es also schon sinnvoll, daß sie im mehrdimensionalen Raum liegt.) Diese Wahrscheinlichkeit müssen wir als prinzipiell beobachtbar ansehen, genau so wie die Lichtintensität als Ortsfunktion in stehenden Lichtwellen. Es ist dann klar, daß die Diagonalelemente der Matrix jeder q -Funktion

$$F_{nn} = \int F(q_k) |\psi(q_1 \dots q_f)|^2 dq_1 \dots dq_f ,$$

¹⁹ London was then in Stuttgart serving as assistant to Paul Ewald at the Institute of Theoretical Physics at the local Technische Hochschule, at the time not a prominent place for quantum theory, and so he could not benefit from private conversations or results that other scholars could take advantage of.

²⁰ Jordan was then in Göttingen and Dirac was visiting Bohr in Copenhagen.

²¹ Pauli to Heisenberg, letter dated October 19, in [VON MEYENN AND WEISSKOPF 1979].

sein müssen, da sie physikalisch "Mittelwert von F im n -ten Zustand" bedeuten. Hier kann man einen mathematischen Witz machen: Es gibt auch eine entsprechende Wahrscheinlichkeitsdichte im p -Raum: Hierzu setze man an (eindimensional formuliert, der Einfachheit halber)

$$\rho_{ik} = \int p \varphi_i(p) \bar{\varphi}_k(p) dp ;$$

$$\frac{i}{\hbar} q_{ik} = - \int \varphi_i \frac{\partial \bar{\varphi}_k}{\partial p} dp = + \int \frac{\partial \varphi_i}{\partial p} \bar{\varphi}_k dp .$$

($\bar{\sim}$ bedeutet konjugiert komplexe Größe; es unterscheidet sich im allgemeinen $\bar{\varphi}_k$ und φ_k nicht nur durch einen konstanten Faktor. Orthogonalität besagt

$$\int \varphi_i \bar{\varphi}_k dp = \delta_{ik}$$

Multiplikationsregel und Relation $pq - qp = -i\hbar 1$ sind erfüllt.)

Sie sehen, daß ich gegenüber der gewöhnlichen Vorschrift die Bildungsgesetze für die Matrizenelemente ρ_{ik} und q_{ik} aus den Eigenfunktionen vertauscht habe. Aus der Matrixrelation des Energiesatzes $p^2/2m + V(q) = E$ gewinnt man

$$\left[\frac{p^2}{2m} + V(-i\hbar \frac{\partial}{\partial q}) \right] \varphi = E\varphi$$

V als Operator gedacht, etwa Potenzreihe in $\frac{\partial}{\partial q}$. Beim harmonischen Oszillator, wo die Hamilton-Funktion symmetrisch in p und q ist, ist auch φ das Hermitesche Polynom. Man kann mit den φ auch Störungstheorie treiben. Auch beim H-Atom muß φ eine einfache Funktion sein, ich habe sie aber noch nicht ausgerechnet. Jedenfalls gibt es also auch eine Wahrscheinlichkeit dafür, daß im n -ten Quantenzustand p_k zwischen p_k und $p_k + dp_k$ liegt, und die ist gegeben durch

$$|\varphi_n(p_1 \dots p_f)|^2 dp_1 \dots dp_f$$

also

$$F(p)_{nn} = \int F(p) |\varphi_n(p)|^2 dp_1 \dots dp_f$$

Da demnach die Diagonalelemente der Matrizen aus den in den Funktionen $\varphi_k(p_1 \dots p_f)$ und $\varphi_k(q_1 \dots q_f)$ enthaltenen kinematischen Aussagen physikalisch folgen, glaube ich nicht, daß Ihre Schwankungsüberlegungen darüber hinaus irgend etwas Neues und für die Deutung der unperiodischen Bewegungen wichtiges sagen können.

According to Pauli (taking over Born's interpretation), if the system is in a state corresponding to the n -th Schrödinger (normalized) eigenfunction, $\varphi(q)$, the probability for the coordinate q to have a value in the interval q and $q+dq$ is given by $|\varphi(q)|^2 dq$. Now, rephrasing Pauli's thought, and using a notation closer to what Jordan will use later in his transformation theory, given two (Hermitian) quantities p and E , one can consider as well the function $\varphi(p, E)$ such that $|\varphi(p, E)|^2 dp$ be the (relative) probability for p to have a value in the interval between p and $p+dp$, given that the value of E

is determined. Pauli's thinking was crucial because it drew attention to a possibility of a *systematic* way of obtaining physical information out of quantum computations (one will find precisely this motivation in Dirac's paper on transformation theory). Eventually, this ended up the bias towards the basis of energy (Hamiltonian) eigenstates making physicists recognize the generality of the eigenvalue problem associated to *any* physical question. Born's interpretation associated to the n -th Schrödinger wave function, i.e. to the wave function representing a state of energy $E = E_n$, the density of probability of position q defined by the square norm $|\varphi_n(q)|^2$. But one can similarly consider a basis of eigenstates for (any) quantity β so, instead of definite energy wave functions, one considers definite β wave functions, say, for $\beta = y$, the functions $\varphi(q, y)$. The second argument of $\varphi(q, y)$ namely y , is running over the spectrum of β (it labels β eigenfunctions). This extension of Born's interpretation had two important consequences on the formal understanding of the situation. First, it emphasized the role of the wave functions which were, prior to this interpretation, considered rather mere handles to formulate the eigenvalue problem. Then it prompted the awareness of the need to concentrate on the relations between the various amplitudes related to different physical questions. This opened the way to the correct appreciation of the linear structure underlying quantum mechanics, and of the role played by orthogonal systems of eigenfunctions associated to different hermitian operators. This is basically the content of transformation theory which unified matrix and wave mechanics; nowadays it is the standard way of exposing the formalism of quantum mechanics.

After the achievements of John von Neumann who put transformation theory on firm mathematical ground, quantum theory reached by 1927 its final mathematical form and scope. After the pioneering times started the period of its intense application to broad domains of quantum chemistry (the understanding of the chemical bonds), solid state physics (magnetism, conduction theory, etc.), and most spectacularly, to rapidly developing nuclear physics and particle physics (quantum field theory). Quantum mechanics extended prodigiously the range of its applications and has since then never failed. In what concerns its basic formalism, it witnessed essentially no further advances, with the exception of Dirac's equation, and the understanding and extension of the role of symmetries. Simultaneously, the 1927 Niels Bohr's influential complementarity manifesto was to start the fierce interpretation debate, and John von Neumann's further explorations of the axiomatic foundations [BIRKHOFF AND VON NEUMANN 1936, JORDAN, VON NEUMANN AND WIGNER 1934, VON NEUMANN 1936] were paving the way for the ambitious programs of its operator algebras and quantum logic axiomatizations.

Conclusion

As I tried to make clear on a few examples, Born's role in the development of quantum mechanics is of prominent importance. Even when he occasionally missed the bigger picture (his missed opportunity, together with Wiener, to discover wave mechanics prior to Schrödinger) or when he did not fully draw the conclusions suggested by his proposals (statistical interpretation), he was *always* in the very leading pack of physicists driving progress in quantum theory.

Besides his exceptional mathematical culture and abilities, Born should also be remembered as a very efficient teacher and collaborator who guided the initial steps or collaborated with many prominent physicists, making Göttingen one of the capitals of quantum theory. Born's students and associates include, besides the most prominent cases of Pauli, Heisenberg and Jordan, other illustrious names such as Enrico Fermi, Vladimir Fock, Walter Heitler, Friedrich Hund, John Oppenheimer, Leon Rosenfeld, Victor Weisskopf and Eugene Wigner. Max Born, in Göttingen, nears here the very remarkable performance of Arnold Sommerfeld, probably the most successful, Munich based, teacher of theoretical physics at the time. Indeed, if one considers the training of a typical young scholar who contributed significantly to quantum theory in the twenties, his first university steps were taken in Munich with Sommerfeld, then continued in Göttingen under Born's guidance, and finally topped with a sejour in Copenhagen to learn from Bohr. This is indeed the training of Pauli and Heisenberg, to quote just the case of two among Born's most famous students. Last but not least, Born, given his pivotal role, had rich epistolary exchanges with other prominent physicists. His correspondence with Einstein [BORN AND EINSTEIN 1971] remains one of the most inspiring exchanges between two remarkable scientists facing their time.

References

- [BIRKHOFF AND VON NEUMANN 1936] G. Birkhoff and J. von Neumann, The Logic of Quantum Mechanics, *Ann. Math.*, vol. 37 (1936), pp. 823-843.
- [BOHR 1918] N. Bohr, The Quantum Theory of Line Spectra, Kopenhagener Akademie, reprinted in Niels Bohr's Collected Works, vol. 3, pp 67-166.
- [BOHR 1934] N. Bohr, *Atomic Theory and the Description of Nature*, Cambridge, Cambridge University Press, 1934.
- [BOHR 1958] N. Bohr, *Atomic Physics and Human Knowledge*, New York, Wiley, 1958.
- [BORN AND BRODY 1921] M. Born and E. Brody, Über die Schwingungen eines mechanischen Systems mit endlicher Amplitude und ihre Quantelung, *Zeit. f. Phys.*, vol.6 (1921), pp. 132-152.
- [BORN AND PAULI 1922] M. Born and W. Pauli, Über die Quantelung gesörter mechanischer Systeme, *Zeit. f. Phys.*, vol.10 (1922), pp. 137-158.
- [BORN 1926A] M. Born, Quantenmechanik der Stossvorgänge, *Zeit. f. Phys.*, vol. 37 (1926), pp. 863-867.
- [BORN 1926B] M. Born, Quantenmechanik der Stossvorgänge, *Zeit. f. Phys.*, vol.38 (1926), pp. 803-827.
- [BORN 1926C] M. Born, Das Adiabatenprinzip in der Quantenmechanik, *Zeit. f. Phys.*, vol. 40 (1926), pp. 167-191.
- [BORN AND JORDAN 1925] M. Born and P. Jordan, Zur Quantenmechanik, *Zeit. f. Phys.*, vol. 34 (1925), p. 858.
- [BORN AND WIENER 1926] M. Born and N. Wiener, Eine neue Formulierung der Quantengesetze für periodische und nicht periodische Vorgänge, *Zeit. f. Phys.*, vol. 36 (1926), p. 174.
- [BORN, JORDAN AND HEISENBERG 1926] M. Born, P. Jordan and W. Heisenberg, Zur Quantenmechanik. II., *Zeit. f. Phys.*, vol. 35 (1926), p. 557.
- [BORN AND EINSTEIN 1971], M. Born and A. Einstein, *The Born-Einstein Letters, Correspondence between Albert Einstein and Max and Hedwig Born from 1916 to 1955, with commentaries by Max Born*, Macmillan, 1971
- [DE BROGLIE 1925] L. de Broglie, Recherches sur la théorie des quanta, *Annales de Physique*, vol. 3 (1925), pp. 22-128.
- [CAZZANIGA 1899] T. Cazzaniga, *Torino Rend.*, vol. 34 (1899), p. 510.
- [DIRAC 1925] P. A. M. Dirac, The Fundamental Equations of Quantum Mechanics, *Proc. Roy. Soc. London (A)*, vol. 109 (1925), p. 642-653.
- [DIRAC 1926A] P. A. M. Dirac, Quantum Mechanics and a Preliminary Investigation of the Hydrogen Atom, *Proc. Roy. Soc. London (A)*, vol. 110 (1926), pp. 561-579.
- [DIRAC 1926B] P. A. M. Dirac, On the Theory of Quantum Mechanics, *Proc. Roy. Soc. London (A)*, vol. 112 (1926), pp. 661-672.
- [DIRAC 1926C] P. A. M. Dirac, The Physical Interpretation of the Quantum Dynamics, *Proc. Roy. Soc. London (A)*, vol. 113 (1926), pp. 621-641.
- [ECKART 1926] C. Eckart, The Solution of the Problem of the Simple Oscillator by a Combination of the Schrödinger and Lanczos theories, *Proc. Nat. Acad. Sci. (U.S.A.)*, vol. 12 (1926), pp. 473-476, and Operator Calculus

and the Solution of the Equations of Quantum Dynamics, *Phys. Rev.*, vol. 28 (1926), pp. 711-726.

[EPSTEIN 1916A] P. Epstein, Zur Theorie des Starkeffektes, *Ann. d. Phys.*, vol. 50 (1916), pp. 489-520.

[EPSTEIN 1916B] P. Epstein, Zur Quantentheorie, *Ann. d. Phys.*, vol. 51 (1916), pp. 168-188.

[EPSTEIN 1922] P. Epstein, Die Störungsrechnung im Dienste der Quantentheorie, I., *Zeit. f. Phys.*, vol. 8 (1922), pp. 211-228, II., p. 305, III., *Zeit. f. Phys.*, vol. 9 (1922), p. 92.

[GOLDSTEIN 1980] H. Goldstein, *Classical Mechanics*, 2d ed., Reading, Mass., Addison-Wesley Pub. Co., 1980.

[GREENSPAN 2005] N. Greenspan, *The End of the Certain World: The Life and Science of Max Born*, New York, Basic Books, 2005.

[HALPERN 1926] O. Halpern, Notiz über die Quantelung des Rotators und die Koordinatenwahl in der neue Quantenmechanik, *Zeit. f. Phys.*, vol. 38 (1926), pp. 8-11.

[HAMILTON 1834] W. R. Hamilton, On a General Method of Dynamics, in *The Mathematical Papers of Sir William Rowan Hamilton*, Cambridge 1931-1967.

[HEISENBERG 1927] W. Heisenberg, Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik, *Zeit. f. Phys.*, vol. 43 (1927), pp. 172-198.

[HILBERT, NORDHEIM AND VON NEUMANN 1928] D. Hilbert, L. Nordheim and J. von Neumann, Über die Grundlagen der Quantenmechanik, *Math. Ann.*, vol. 98 (1928), pp. 1-30, reprinted in Taub 1961, vol. 1, pp. 104-133.

[HUND 1967] F. Hund, *Geschichte der Quantentheorie*, Bibliographisches Institut, Hochschultaschenbücher Verlag, 1967.

[VON MEYENN AND WEISSKOPF 1979], A. K. von Meyenn and V. F. Weisskopf (eds), *W. Pauli Wissenschaftlicher Briefwechsel 1919-1929*, New York, Springer, 1979.

[JACOBI 1866] C. G. J. Jacobi, *Vorlesungen über Dynamik*, supp. vol. to C. G. J. Jacobi *Gesammelte Werke*, A. Clebsch ed., Leipzig, 1866, reprint 1969.

[JAMMER 1966] Max Jammer, *The Conceptual Development of Quantum Mechanics*, New York, Mc Graw-Hill Book Company; 1966.

[JAMMER 1974] Max Jammer, *The Philosophy of Quantum Mechanics*, New York, 1974, John Wiley and Sons.

[JORDAN 1926A] P. Jordan, Über kanonische Transformationen in der Quantenmechanik, *Zeit. f. Phys.*, vol. 37 (1926), pp. 383-386.

[JORDAN 1926B] P. Jordan, Über kanonische Transformationen in der Quantenmechanik. II, *Zeit. f. Phys.*, vol. 38 (1926), pp. 513-517.

[JORDAN 1926C] P. Jordan, Über eine neue Begründung der Quantenmechanik, *Gött. Nachr.*, (1926), pp. 162.

[JORDAN 1926D] P. Jordan, Über eine neue Begründung der Quantenmechanik, *Zeit. f. Phys.*, vol. 40 (1926), pp. 809-838.

[JORDAN 1927] P. Jordan, Über eine neue Begründung der Quantenmechanik. II., *Zeit. f. Phys.*, vol. 44, (1927), pp. 1-25.

[JORDAN, VON NEUMANN AND WIGNER 1934] P. Jordan, J. von Neumann and E. Wigner, On an Algebraic Generalization of the Quantum Mechanical Formalism, *Ann. Math.*, vol. 35 (1934), pp. 29-64.

[LANCZOS 1926] K. Lanczos, Über eine feldmässige Darstellung der neuen Quantenmechanik, *Zeit. f. Phys.*, vol. 35 (1926), pp. 812-830.

[LANCZOS 1986] C. Lanczos, *The Variational Principles of Mechanics*, 4th ed., New York, Dover Publications, 1986.

[LÉVY 1922] P. Lévy, *Leçons d'analyse fonctionnelle*, Paris, Gauthier-Villars, 1922.

[LONDON 1926A] F. London, Über die Jacobischen Transformationen der Quantenmechanik, *Zeit. f. Phys.*, vol. 37 (1926), pp. 915-925.

[LONDON 1926B] F. London, Winkelvariable und kanonische Transformationen in der Undulationsmechanik, *Zeit. f. Phys.*, vol. 40 (1926), pp. 193-210.

[MEHRA AND RECHENBERG 1982] J. Mehra and H. Rechenberg, *The Historical Development of Quantum Theory*, New York, Berlin, Heidelberg, Springer, vol. 2, vol. 3, vol. 4, (1982), vol. 5, (1987).

[VON NEUMANN 1927A] J. von Neumann, Mathematische Begründung der Quantenmechanik, *Gött. Nachr.*, (1927), pp. 1-57, reprinted in Taub 1961, vol. 1, pp. 151-207.

[VON NEUMANN 1927B] J. von Neumann, Wahrscheinlichkeitstheoretischer Aufbau der Quantenmechanik, *Gött. Nachr.*, (1927), pp. 245-272, reprinted in Taub 1961, vol. 1, pp. 208-235.

[VON NEUMANN 1927C] J. von Neumann, Thermodynamik quantenmechanischer Gesamtheiten, *Gött. Nachr.*, (1927), pp. 273-291, reprinted in Taub 1961, vol. 1, pp. 236-254.

[VON NEUMANN 1932] J. von Neumann, *Mathematische Grundlagen der Quantenmechanik*, Berlin, Springer 1932; english translation, *Mathematical Foundation of Quantum Mechanics*, Princeton, Princeton Univ. Press, 1955.

[VON NEUMANN 1936] J. von Neumann, On an algebraic generalization of the quantum mechanical formalism, *Mathematiceskij Sbornik-Recueil Mathématique*, vol. 1 (1936), pp. 415-484, reprinted in Taub 1961, vol. 3, pp. 492-559.

[PAULI 1927] W. Pauli, *Zeit. f. Phys.* vol. 41 (1927), p.21.

[PINCHERLE 1897] S. Pincherle, Mémoire sur le calcul fonctionnel distributif, *Math. Ann.*, vol. 49 (1897), pp. 323-382.

[PINCHERLE 1905] S. Pincherle, Funktionaloperationen und Gleichungen, in *Encyclopedia der mathematischen Wissenschaften*, vol. II.

[SCHRÖDINGER 1926ABCD] E. Schrödinger, Quantisierung als Eigenwertproblem (Erste Mitteilung), *Annalen der Physik*, vol. 79 (1926), pp. 361-376; b: Zweite Mitteilung, vol. 79, pp. 489-527; c: Dritte Mitteilung, vol. 80 (1926), pp. 437-490; d: Vierte Mitteilung, vol. 81 (1926), pp. 109-139.

[SCHRÖDINGER 1926E] E. Schrödinger, Über das Verhältnis der Heisenberg-Born-Jordanschen Quantenmechanik zu der meinen, *Annalen der Physik*, vol. 79 (1926), pp. 734-756.

[SCHWARZSCHILD 1916] K. Schwarzschild, *Berl. Ber.*, 1916, p. 548.

[SINGH AND RIESS 2013] R. Singh and F. Riess, Belated Nobel prize for Max Born FRS, *Indian Journal of History of Science*, 48.1 (2013) 79-104.

Kurzmitteilung - Short Announcement

Weltraum Sommerschule Alpbach 2016 in Österreich erforscht Globalen Wasserkreislauf

60 junge Wissenschaftler aus ganz Europa werden für die Teilnahme an der renommierten Planungsschmiede für zukünftige Satellitenmissionen ausgewählt. Die Teilnehmer sind heuer aufgerufen, neue und innovative Satellitenmissionen zum Thema „Globaler Wasserkreislauf“ zu entwickeln und einer Jury von ExpertInnen vorzustellen.

Die Sommerschule findet vom 12. - 21. Juli 2016 in Alpbach (Tirol) statt.

Weitere Informationen:

http://www.esa.int/ESA_in_your_country/Austria/Weltraum_Sommerschule_Alpbach_2016_in_Oesterreich_erforscht_Globalen_Wasserkreislauf

Bewerbungen sind möglich bis 31. März 2016 unter:

www.summerschoolalpbach.at

Young Physicists Forum 2015: Astronomy

Armin Fehr, former president of the Young Physicists Forum (YPF)

After last year's visit to the Technorama in Winterthur with a YPF topic on energy issues, we decided to focalize this year on astronomy. Our event took place on the 2nd and 3rd of October 2015 in Bern.

Our goal is to encourage exchange between physics students from different universities in Switzerland and to awaken their interest each time in another specific topic.

Arrival and welcome

We met on Friday at 18:00 at the train station in Bern and walked together to the youth hostel just below the House of Parliament. The students then had time to settle down and move into their rooms. After the delicious dinner we had some time to get to know each other. Most students then set off to explore the city.

Presentations

Saturday morning after breakfast, we left the hostel heading to the university, where we listened to the talks.

Prof. Dr. *Nicolas Thomas* from the University of Bern started with a presentation about the latest findings of the Rosetta mission. It was fascinating to hear about the diversity of surface properties and the shape of a small body like 67P/Churyumov–Gerasimenko. He managed to explain everything in a remarkable understandable and entertaining way. After this phenomenal start, Prof. Dr. *Samuel Krucker* from the University of Applied Sciences and Arts Northwestern Switzerland (FHNW) continued with the STIX hard X-ray telescope on ESA's Solar Orbiter, which was built under his lead. He explained the physical background of the sun's heliosphere, why hard X-rays are used as diagnostic and how the X-ray images are created.

After a coffee break, Prof. Dr. *Adrian Jäggi* from Bern introduced us to the working principles and usefulness of Satellite Laser Ranging (SLR). This was the perfect preparation for the afternoon visit to the Zimmerwald Observatory, where SLR is a dominating topic. This type of geodesic measurement allows for example the quantitative determination of the ice loss on Greenland.

Last but not least, Dr. *Frédéric Courbin* from EPFL told us about the ESA Euclid mission and its importance for cosmology and the giant amount of data it will provide. For example, it will produce images of around 300'000 lensing galaxies with arc and rings, compared to some dozens known today.



Photos: Oleh Yermakov, EPFL

Guided Tour through Zimmerwald Observatory

After this highly interesting morning, we went by bus to the village of Zimmerwald and stopped for lunch at the Gasthof Löwen. Thereafter, we walked to the observatory, where we were split into three groups and got to the different guides, all active at the University of Bern.

PD Dr. *Andreas Verdun* told us about the rich history of the observatory, while Dr. *Pierre Lauber* showed us the SLR part of the observatory. We could look at the laser system and go on the roof to see the laser telescope. *Emiliano Cordelli* for his part led us in the big dome and told us about other topics being studied at the Zimmerwald observatory, like for example the issue of space debris.

At the end of this interesting day, we made a group photo of the forty-two participants and hurried down the hill to the bus through a magnificent autumnal landscape, bringing us back to Bern.



Conclusion

It's fascinating to see that Switzerland has such an important role in so many different astronomical experiments and missions. There were a lot of different fields from which we could easily have found other top-notch speakers, so that it was hard to concentrate on only four speeches.

This is also the reason why our timetable was pretty crammed. We had to hasten from one appointment to another and it was (especially for us organisers!) a bit stressful. Therefore at a next event we will schedule more time to reflect and discuss about the things heard. Nevertheless, the students showed great interest and asked wide-ranging questions, which yielded interesting ideas.

Our event was a big success. There was a stunning total of around sixty registrations. Unfortunately, we had to refuse some students, as the number of beds in the youth hostel was limited. Especially, there was a big interest in the event from the EPFL students. Two thirds of the participants were French speaking. We received mainly positive feedback and are looking forward to organising a great event in 2016. We will then also reuse our website www.youngphysicistsforum.jimdo.com, which was very useful for promoting the event.

The Young Physicists Forum wants to thank the SPS and SCNAT for their funding. We are thankful that we had the opportunity to organise this event. Further thanks go to all the people who helped organising and contributing to the event. We especially would like to thank the speakers and guides for their effort and time.

Review Symposium 100 Years of General Theory of Relativity ETH Zürich, 12. – 14. November 2015

Hans Rudolf Ott

In retrospect, November 1915 was an important and decisive period in the history of physics or better, of science in general. It was the period when Albert Einstein, as an employed member of the Prussian Academy of Sciences in Berlin, struggled for the formulation of the General Theory of Relativity which, at the same time, was a new Theory of Gravitation. These were the final days of a year-long pursuit of an idea that struck him in 1907 when he was still a clerk at the Federal Patent Office in Bern. During the next years, he was mainly occupied with problems that were related to the then new concept of quanta. Nevertheless, he developed a pretty good view on the physics aspects of a generalization of his theory of relativity of 1905 (now called the special theory of relativity) but soon realized that his competences in mathematics were simply not adequate to achieve a rigorous formulation of the theory. The situation changed decisively when he took office as a full professor at ETH in Zurich at the beginning of August 1912. He sought and found support from his study-friend and now professor of mathematics, also at ETH, Marcel Grossmann. During the next year, they worked together and in early September of 1913, presented a draft Theory of General Relativity and Gravitation at the fall meeting of the *Schweizerische Naturforschende Gesellschaft* in Frauenfeld. The reasons why it took Einstein another two years and two months of very hard work to complete his mission in Berlin is now history.

Since extremely important steps forward in that entire enterprise were made while Einstein was in Switzerland, it seemed natural to celebrate the 100th anniversary of his triumph in some form in this country. The main idea was to invite a number of highly-recognized experts who are familiar with different aspects of the theory and its later development and willing to share their wisdom with a general audience, not necessarily specialists in the field but interested in getting a closer look at what may be regarded as one of the most outstanding intellectual achievements in the history of human thinking and science.

The idea finally resulted in a Symposium entitled „100 Years of General Theory of Relativity“ at the ETH in Zurich, spon-

sored by various institutions. A preregistration resulted in more than 400 potential participants who, in retrospect, seem to have participated in parts or over the entire duration of the event from Thursday, November 12 to Saturday, November 14, 2015. Paying tribute to the expected predominantly local audience and depending on the speakers' native language, the lectures were presented in either English or German.

The first half day, scheduled for the afternoon on Thursday, was dedicated to two lectures, given by *Sergiu Klainerman, Princeton* and *Jonathan Luk, Cambridge, UK*, concentrating on mathematical problems related with the formal description of black holes and questions of their physical reality. It was shown that mathematical aspects of the theory continue to be of interest and pose problems, which are obviously difficult to solve.



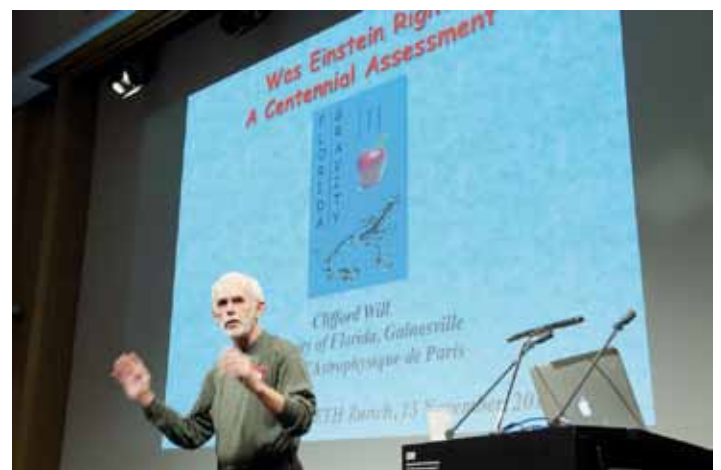
In the first lecture, *Sergiu Klainermann* discusses an important question.

The morning session of the next day concentrated on historical aspects. The first contribution, by *Domenico Giulini, Hannover*, covered the genesis of the theory and the lecture of *Tilman Sauer, Mainz*, summarized the later development in the form of a biography of the theory.

The first afternoon session started with the question of *Cliff Will, Florida*: "was Einstein right"? The answer was given by discussing examples of Einstein's predictions and their



Opening of the Symposium, Friday November 13, 2016.



Clifford Will explains

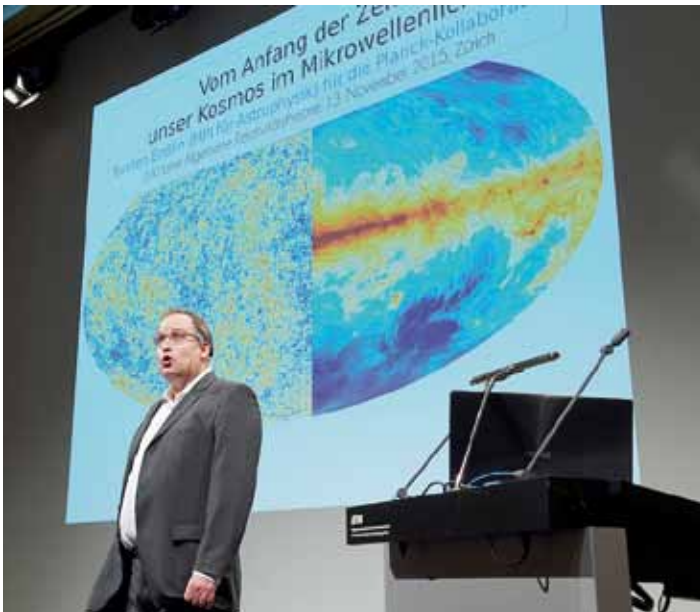
experimental verifications – then and during the past 100 years. This overview was complemented by the next contribution of *Sam Finn, University Park, Pennsylvania*, who summarized research efforts related to the gravity-induced curvature of space-time and the search for gravitational waves over the last 100 years.

In the second afternoon session, *Ruth Durrer, Geneva*, discussed the role of relativity in cosmology and gave an overview on the evolution of the known universe, its expansion and its, to a large extent, unidentified content in the form of dark matter and dark energy. Next, *Paul Townsend, Cambridge, UK* made contact between relativity, gravity and more modern ingredients of theoretical physics such as strings, branes and other exotic mathematical objects. He also offered an explanation of why Einstein's conjecture that gravity and quantum mechanics are incompatible, is still valid.



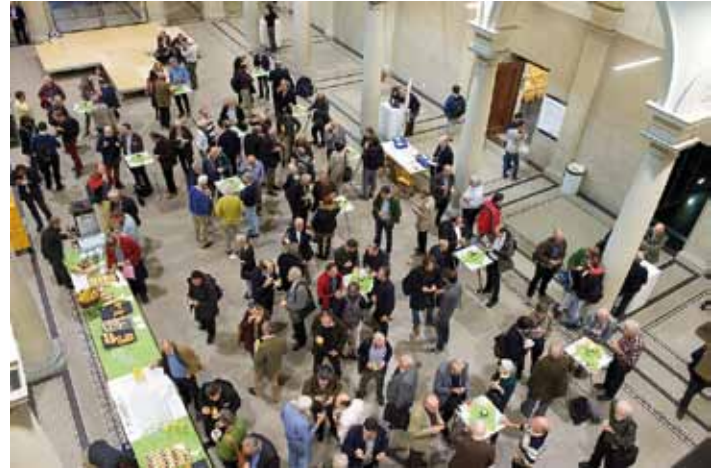
Ruth Durrer answers questions from the audience.

On Friday evening, the programme offered a public lecture on „The Beginning of Time“ by *Torsten Ensslin, Garching*. He described, in simple terms, what can be learned from observations of the so called cosmic background radiation, a surviving feature of the early universe, with highly sophis-



Public Evening Lecture by Torsten Ensslin

ticated experimental instrumentation on satellites and the subsequent involved analysis of the recorded data. The reaction of the audience indicated that the right words fell on fertile ground.



Refuelling and Discussions

The first lecture on Saturday morning was given by *Thomas Janka, Garching*, who gave a richly illustrated view on Supernovae explosions that, under special circumstances, follow gravitational collapses of stars. He discussed the processes of dying stars and the important role of neutrinos in that that process. Subsequently, *Reinhard Genzel, Garching and Berkeley*, embarked on the problem on how the existence of a black hole as, e.g., in the center of our galaxy, is proven. He emphasized the availability and role of large telescopes and the ongoing developments of still larger and hence more resolving instrumentation. The third lecture of the morning by *Joachim Wambsganss, Heidelberg*, gave an overview on the history of gravitational bending of light rays and the later recognized opportunities of the so-called gravitational lensing effect in modern explorations of the universe, including the discovery of extrasolar planets in far away galactic systems.

In the first lecture of the afternoon session, *Urs Hugentobler, Munich* emphasized the importance of measurements of time differences in modern geodesy based on the global navigation satellite system (GNSS) and consequently the role of clocks and relativity in daily life. The last but certainly not least contribution to the programme was delivered by *Bernd Brügmann, Jena*. He covered the relatively new area of numerical approaches to relativity, in particular the treatment of the solution of the generally relativistic two-body problem for binary black holes. In addition he demonstrated how numerical simulations may lead to theoretical predictions in relation with the discovery of gravitational-wave signals.

Taken all together and from reactions of the audience, it seems that the Symposium fulfilled the original intention.

Note: A major part of the lectures is, in form of a video or with the presented slides, available on einstein.phys.ethz.ch.

Resumée du symposium "Grains de lumière", 14 novembre 2015 à Sion

La **Société Valaisanne de Physique** a été fondée en 1995 et rassemble tous les amateurs de physique quel que soit leur parcours et compte aujourd'hui plus de 80 membres. Elle organise notamment chaque année de nombreuses conférences et visites en lien avec la physique, ainsi qu'un symposium annuel à Sion. Notre site web www.valaisphysique.ch peut être consulté pour une liste exhaustive de nos activités.

Le symposium de la Société Valaisanne de Physique de cette année 2015 a revêtu un caractère tout à fait particulier puisque nous célébrions les **20 ans** de la Société Valaisanne de Physique, ainsi que **l'Année Internationale de la Lumière**. Dans cette optique, nous avons adapté la forme de ce symposium afin de pouvoir accueillir trois orateurs d'exception pour former une série de trois conférences intitulées « Grains de lumière ».

La première conférence « Clin d'oeil à l'optique » par *Martial Geiser* de la HES-SO Valais-Wallis nous a tout d'abord fait un historique des bases générales de l'optique, de la vision et de son interprétation au cours des âges. D'Euclide à Huygens en passant par Ibn al-Haytham ou encore Fresnel, toute la compréhension que nous en avons aujourd'hui a passé par de nombreuses étapes jalonnées de nombreux savants et scientifiques. L'optique a aujourd'hui plusieurs visages, diverses utilisations dans des domaines aussi variés que l'astrophysique, la télévision, la santé et en particulier le fond de l'oeil. Martial Geiser a présenté les nombreuses techniques utilisées dans le domaine de l'ophtalmologie qui

permettent d'allier les pouvoirs du photon à la médecine de pointe.

La deuxième conférence intitulée « Les lasers dans tous leurs états » par *Benoît Devaud*, professeur à l'EPFL, emboîtait le pas à la précédente conférence et nous a décrit une multitude de lasers différents que l'on retrouve partout dans la vie courante. Auparavant, l'histoire rocambolesque de la guerre des brevets du laser, conflit qui a duré pratiquement 20 ans, nous a été narrée par Benoît Devaud. Après un bref rappel sur le fonctionnement d'un laser, toute une panoplie de lasers nous a été présentée, allant des lasers miniatures de l'ordre du micromètre au plus gros laser de 500 TW du National Ignition Facility situé au Lawrence Livermore National Laboratory en Californie.

La dernière conférence « Cryptographie et Téléportation - Quand la lumière se fait quantique » par *Grégoire Ribordy*, directeur général de ID Quantique, nous a présenté la cryptographie quantique et l'utilisation du photon comme vecteur garant d'une transmission sûre d'informations. En se basant sur un protocole de partage symétrique de clé d'encryption et l'état intriqué de photons comme indicateur de sécurité et d'invulnérabilité, ID Quantique ouvre la voie à une nouvelle ère dans le milieu de l'information et de sa gestion. Le photon et son état fondamentalement quantique lui permet également d'être téléporté et un avenir radieux de réseau global quantique s'ouvre à nous avec ces technologies.

Thomas Produit, Société Valaisanne de Physique

Séminaire Dautreppe Photonique 2015

Antoine Pochelon¹, Patricia Segonds², Lucien Besombes², Gérard Chouteau³, Pierre Molho²

¹ SSP Lausanne; ² Institut NÉEL-CNRS-UJF Grenoble, ³ SFP-Alpes Grenoble

Depuis 1969, la section grenobloise de la Société Française de Physique (SFP) organise annuellement le « séminaire Dautreppe » réunissant des experts sur un thème choisi de la physique pour réaliser une synthèse pédagogique de l'état de l'art. Pas étonnant dès lors qu'avec cette ambition le séminaire porte le nom de Daniel Dautreppe – un compagnon de Louis Néel - quand on sait que « c'était un homme remarquable, alliant, à une compétence évidente en physique, un grand souci de l'humain et, dès le début, un grand talent de communication et de pouvoir de conviction »¹.

Savoir communiquer une synthèse pédagogique de l'état de l'art dans un domaine est donc bien au cœur de la motivation de ce séminaire. Les orateurs, issus du monde académique ou du tissu industriel sont choisis pour leur qualité pédagogique, dans le but de s'adresser aux doctorants, post-doctorants, aux techniciens et ingénieurs, aux chercheurs et enseignants-chercheurs, ainsi qu'aux industriels. Afin de pouvoir communiquer avec ce large public, l'enseignement

se doit d'être très progressif et pédagogique, en développant tout d'abord les aspects fondamentaux pour fournir les outils conceptuels généraux; puis en spécialisant du côté des applications. Parmi les thèmes abordés ces dernières années par le séminaire Dautreppe, rappelons « Matière et symétries » (2014), « les phases exotiques » (2013), « Quasi-cristaux » (2012), et « Supraconductivité » (2011).

Pour 2015 qui a été l'année internationale de la lumière (IYL2015), le thème de la lumière s'imposait et les organisateurs du séminaire Dautreppe l'ont voulu sur la « Photonique: générer, contrôler, détecter la lumière »². Ils ont voulu aussi que pour la première fois il soit organisé en partenariat avec la Société de Physique Suisse (SSP). Le séminaire s'est tenu sur les 7 - 10 décembre 2016 à Grenoble sur le campus CNRS de Grenoble. Les thèmes généraux ont été distribués sur quatre journées : 1) Sources cohérentes, 2) Optoélectronique, optique intégrée, 3) Optique quantique, nanophotonique 4) Imagerie, spectroscopie. La conférence en quelques chiffres, c'était typiquement 8 présentations d'une heure par jour incluant des questions-réponses, il y

¹ Une bibliographie de Daniel Dautreppe, créateur du DRF, rédigée par M. Belakhovsky, ancien président SFP-Alpes à l'occasion du "Séminaire Dautreppe" de 2005 (2 pages). http://inac.cea.fr/com_scientifique/Contributions_histoire/Files/MB_Daniel_Dautreppe_SFP.pdf

² Voir : <http://dautreppe.photonique.grenoble.cnrs.fr/>

La section locale Alpes de la SFP correspond à l'académie de Grenoble. Elle comprend 5 départements: Ardèche (07), Drôme (26), Isère (38), Savoie (73), Haute-Savoie (74) et compte plus de 200 adhérents. Ses adhérents sont issus du monde académique et du tissu industriel lié au bassin grenoblois. Les domaines de spécialités des différents membres du bureau sont représentatifs des thématiques scientifiques présentes dans la région.

Les actions de la section locale ont pour but de donner de la cohésion à la communauté scientifique grenobloise. Elle propose et organise pour cela

- le *38 de Sciences* : un **calendrier en ligne** de tous les événements scientifiques dans la région de Grenoble (anciennement les "38 de Physique et de Biologie/Chimie").

- les *Questions de Physique* : des conférences sur un large éventail de sujets liés à la physique. Ces conférences sont destinées à tous physiciens et toutes personnes intéressées par la physique.

- le *Séminaire Daniel Dautreppe* : ces écoles thématiques sont organisées une fois par an, le thème variant chaque année. Elles ont pour but de donner aux chercheurs une introduction solide à un sujet donné. Ils sont particulièrement destinés à des **étudiants de thèse**.

Pour suivre la section Alpes, rendez-vous sur la page facebook: <https://www.facebook.com/SFP.Alpes>

avait une centaine de participants, 25 conférenciers. Les étudiants du bassin grenoblois qui se sont regroupés en un club nommé EOS/SFO Alpes Student Club ont assuré l'accueil des participants et organisé une session de 20



Les organisateurs du séminaire Dautreppe 2015, Patricia Seconds et Lucien Besombes

posters. Les séminaires Dautreppe sont essentiellement organisés dans le cadre de la section Alpes de la SFP qui regroupe 200 adhérents du bassin grenoblois. C'est la première fois que la SSP est invitée à y participer au niveau du comité scientifique, nos deux sociétés explorant les activités communes pouvant bénéficier aux physiciens des deux sociétés.

La langue officielle jusqu'à maintenant a toujours été le français, avec les supports de présentation (transparents, poster) en anglais. Avec une forte préférence pour le français, le libre choix de la langue a été laissé aux orateurs pour leur exposé ou leur poster.

Rappelons que Grenoble est le deuxième centre scientifique en France, juste derrière Paris - alors, quand la section SFP-Alpes y organise le sé-

minaire Dautreppe, ce dernier est dans son milieu et déplace du monde. Au fil des années, il s'est illustré comme un très bel événement avec d'excellents séminaires présentés dans un amphithéâtre confortable, et des pauses café bien organisées où les participants pouvaient profiter de quelques stands de littérature de la SFP. Il y a aussi – ce qui stimule les nouvelles rencontres - des repas de midi debout autour de tables hautes dans un restaurant situé à proximité. Il faut souligner qu'au CNRS à Grenoble, la salle où se tient la pause porte le nom d' "espace de convivialité", un nom chargé de sens ! Notons qu'un crédit ECTS est accordé aux étudiants et que pour la première fois ils ont été impliqués dans l'organisation du séminaire.



Jonathan Home, ETHZ, ouvrant la matinée de la journée Optique quantique, Nanophotonique.
© A. Pochelon

La participation suisse, tout-à-fait adéquate au niveau des conférenciers (3/24), avec la participation de Thomas Südmeyer, UNINE, Hugo Zbinden, UNIGE et Jonathan Home, ETHZ, est restée faible au niveau des étudiants et post-docs, à qui ce séminaire est prioritairement destiné. La raison première apparaît bien être la langue. Qu'on l'aime ou qu'on ne l'aime pas, l'anglais est devenu la langue dominante des cours au niveau universitaire en Suisse ou pour le moins à l'EPFL, où les cours de master et de doctorat sont en anglais.

Même les cours de bachelor (3ème année) peuvent y être en anglais. Par contre par exemple à l'UNIFR au niveau master, seuls certains programmes d'études ne sont offerts qu'en anglais. Mais ceci n'a pas encouragé la participation de certaines écoles doctorales qui ont affiché un enthousiasme mesuré car "leurs étudiants, souvent étrangers, parlent l'anglais". Il y a le risque pour le séminaire Dautreppe que si on veut l'ouvrir d'avantage aux étudiants et post docs étrangers, on le ferme d'avantage aux ingénieurs et techniciens des laboratoires grenoblois, qui sont moins anglophones mais néanmoins intéressés, en particulier pour des thématiques comme celle de ce dernier Dautreppe. La discussion reste donc ouverte. En plus des étudiants, qui représentent 70% de la participation, il y a aussi tout un plus large public de physiciens qui trouvent dans ce séminaire l'occasion de s'ouvrir sur un sujet d'actualité et de l'approfondir.

La collaboration SFP- SSP autour du séminaire Dautreppe offre des opportunités de rapprochement des physiciens de nos deux sociétés à travers l'organisation pratique de ce séminaire, qui pourrait même bien à l'occasion se rapprocher de la Suisse.

Les enfants sont fascinés par la science de la lumière

Minh Quang Tran, Président de la SSP



INTERNATIONAL
YEAR OF LIGHT
2015

A l'occasion de l'International Year of Light, plus de 50 manifestations ont été organisées en Suisse. Elles couvraient tous les domaines. Bien entendu, la majeure partie d'entre elles portaient sur la science, mais elles portaient aussi sur des aspects artistiques ou sociaux (pour une liste, <http://www.light2015.org/Home/Event-Programme.htm>

[/?tab=3&filter=true&category=cafe1dea-3958-41ac-b5b2-1b5d8834f7f5](http://www.light2015.org/Home/Event-Programme.htm?tab=3&filter=true&category=cafe1dea-3958-41ac-b5b2-1b5d8834f7f5))

Un aspect important de certaines manifestations a été l'initiation des enfants et des jeunes à la science. C'est dans ce cadre et avec cette vision d'intéresser les enfants et les adultes, que l'Ecole Polytechnique Fédérale de Lausanne (EPFL) a organisé le 07 Novembre 2015 une journée intitulée « Lumière sur la lumière ». Ouverte à toutes et tous, petits et grands, la journée proposait des **conférences pour adultes** et des **ateliers pour les enfants** de 7 à 13 ans.



Encadrés par toute une équipe d'étudiant-e-s, 160 enfants ont participé à **différents ateliers pour découvrir le thème de la lumière** sous différentes facettes et par petits groupes: fabriquer un périscope pour appréhender la réflexion de la lumière dans un miroir, recomposer la lumière blanche en fabriquant une toupie arc-en-ciel, produire de la lumière à partir de réactions chimiques, souder une lampe de poche fonctionnant grâce à la lumière, découvrir la lumière invisible, fabriquer un cadran solaire. Ces ateliers ont été conçus et préparés spécialement pour eux par le Dr. Daniele Mari et la



Section de Physique de la Faculté des Sciences de Base, l'association Photonics Chapter EPFL et le Service de Promotion des Sciences.

Entre ces ateliers, qui les a occupés de 10:00 à 15:00, les enfants ont pu se régaler et reprendre des forces grâce aux généreux plats de pâtes préparés par l'Ornithorynque.

Pour finir en beauté la journée, Christophe Perez, chasseur d'aurores boréales et médiateur scientifique, les attendait au forum Rolex Learning Center de l'EPFL pour leur parler de ce majestueux phénomène, en présence de leurs parents qui avaient assisté aux conférences.

Un grand merci aux conférenciers qui, en 15 minutes chrono, ont abordé la lumière sous différents angles: technique avec le Dr. Patrick Heinstejn du Centre Suisse d'Electronique et Microtechnique, théologique avec le Prof. Thomas Römer de l'Université de Lausanne, astrophysique avec Dr. Anaïs Rassat de l'EPFL, médical avec le Prof. Hon. Hubert Van den Bergh de l'EPFL, artistique avec Mme. Bettina Tschumi du Musée de Design et d'Arts Appliqués Contemporains de Lausanne. Les questions du public et les points de vue des intervenants ont suscité curiosité, intérêt et ouverture sur d'autres mondes intéressants.

Comme le disait un enfant à sa mère, « Ca, c'est une journée qu'il n'oubliera jamais. »

Source:

Texte sur la journée « Lumière sur la Lumière » par le Service de Promotion des Sciences

<http://actu.epfl.ch/news/une-journee-radieuse-et-des-sourires-illumines/>, ainsi que quelques témoignages: <http://sps.epfl.ch/AnneelLumiere>. Et des photos: <http://mediatheque.epfl.ch/album/display/899/page/1>



Les participants après la remise des certificats. Au fond, quelques conférenciers et organisateurs.

Toutes les photos: ©: EPFL - Murielle Gerber

IYL 2015, Swiss Closing Ceremony at EPFL 5 Dec 2015

Antoine Pochelon and Minh Quang Tran

On December 5, the EPFL hosted an event to promote the progress and promise of light technologies and research. The program marked the Closing Ceremony of the International Year of Light in Switzerland and featured the latest in photonics as well as leading scientists to promote improved public understanding of the central role of light in the modern world.

Let us first remember that the International Year of Light and Light-Based Technologies (IYL 2015; www.light2015.org) is a global initiative adopted by the United Nations to raise awareness of how optical technologies promote sustainable development and provide solutions to worldwide challenges in energy, education, agriculture, communications and health. The first proposal stemmed from Ghana in 2012, was relayed by New Zealand, and was finally able to group 85 countries around this theme. Christophe Rossel, the president of EPS, recalled some cardinal dates of the evolution of ideas around light, like:

- 1015 Ibn Al-Haytam's book on optics
- 1865 Maxwell's equations
- 1915 General relativity
- 1965 Cosmic Microwave Background (CMB) observation

This celebration brought together specialists from Google X, Bell Labs, Intel, Philips, Heptagon, UNESCO, Solar Impulse or IBM Research among others, as well as people from the academy, to foster learning, inspiration and wonder (www.light2015.ch).

Different events also punctuated this year IYL2015 in Switzerland. Among them outreach events like *Scientifica* in Zürich (ETHZ & UZH) and *Lumière sur la Lumière* (see previous page) at EPFL, which marked the public: "Ça, c'est un jour que mon fils n'oubliera jamais", told a mother to Minh Quang Tran, president of the SPS. About the progress in lighting equipment, Quang remembered us that as a child in Vietnam he had to live with petrol lamps to study in the evenings, not only painful for the eyes but also quite toxic, thus witnessing the tremendous and beneficial progress of light technologies.

We heard also about the progress in augmented vision glasses, in medical technologies, the fantastic increase in capacity of optical fibers linking continents and computers, the light making education possible in development countries or social activities in the evening that would simply not be possible without light. Further, the LEDification of lighting, combined with digitization, offers complete new possibilities to transmit information.

Joe Nimela from UNESCO and member of the steering committee of IYL2015 under-

lined the important role of light in education since light is essential for studying after sunset. When you look at overnight pictures of Africa from space you see nearly no light! LEDs and PV panels are thus of great help and a promise, since "Education is the most powerful weapon to change the world", he remembered.

The most magic moment in the evening was certainly brought by Ralph Light, playing music with a laser beam harp, both a technical and musical performance. His interpretation of *Eine kleine Nachtmusik* by Mozart was just perfect.

Jean-Pierre Wolf described some quantum physics magic's: on one side how two red photons combine into one blue photon, and on the opposite how one photon can go through two slits – as long as you don't try to ask through which one. Based on the analysis of the CMB - the remaining light of the early universe - Anaïs Rassat explained that we know only 5% of the constituents of the universe and that the nature of the remaining 95% is unknown. General relativity is an example of fundamental research activity, apparently far from practice, but which, less than a century later, can give rise to practical objects like GPS and portable phones. The use of caustics to produce images from refraction or reflection of light was intriguing: a nice inverse problem! A video showed the challenges met by the Solar Impulse plane. Markus Rossi showed all kind of geometrical applications like 3D imaging, the fabrication of optical microstructures like diffractive optics to be integrated in larger micro-optical devices.

As a conclusion to this enlightening evening, Christoph Harder, president of Swiss Photonics, presented a video on the industrial use of lasers, "From invention of laser to the photonic industry, machining with laser light with highest speed and precision".



Ralph Light playing on his laser beam harp and enchanting the audience.
© Clément Javerzac-Galy.

IYL 2015 - Licht und Natur

Die angestrebten Aktivitäten der UNESCO im Rahmen des Internationalen Jahr des Lichts wurden in die Themenfelder Licht-Technologie, Wissenschaft des Lichts, Licht in der Natur, Licht und Kultur sowie in themenübergreifende Aktionen gegliedert, die alle die zentrale Bedeutung von Licht aufzeigen sollten. Es zeigt sich nun nach Abschluß des Jahres 2015, dass der Hauptanteil der Veranstaltungen den beiden technisch-wissenschaftlichen Kategorien zugeordnet werden kann, während zumindest in der Schweiz Beiträge aus der künstlerischen Szene unterrepräsentiert sind. Das ist bedauerlich und entspricht auch nicht den Intentionen von IYL2015; aber es ist auch nicht verwunderlich, denn das Zusammenwirken überfordert oft (noch) beide Seiten, Künstler sowohl wie Wissenschaftler. Es gibt aber auch löbliche Gegenbeispiele:

Während wir das Phänomen Licht spektakulär in Naturerscheinungen wie z.B. Sonnenuntergängen seit alters her geniessen, ermöglicht die Verwendung neuartigen Lichtes die Natur so zu verfremden, dass sich ihr Charakter in neuartiger und anregender Weise dem Betrachter erschliesst. Im Folgenden sei eine Licht-Performance der Künstlerin Petra Krischke aus dem Jahre 2014 vorgestellt, in der sie, die Ideen von IYL2015 vorwegnehmend, den uns vertrauten Ansatz, mit Licht spezielle Naturreaktionen auszulösen, in einer originellen Aktion umsetzte.

Die Künstlerin hatte dazu in aufwendiger Installationsarbeit 3000 LEDs an Glasfaserbündel gekoppelt und das Ensemble als photonische Wiese unter Bäume gelegt. Das grüne, leicht blauhaltige Kunstlicht erreichte den Betrachter auf verschiedenen Pfaden: Zum einen leuchteten die Faserbündel als ein für sich wogendes Kollektiv, zum andern verfälschten sie das Naturgrün der bestrahlten Baumblätter in ungewohnter Weise, und zusätzlich erfolgte eine diffuse Reflexion mit wiederum leicht anderem Grünstich durch die Bodenfolien. Der optische Eindruck, geprägt durch unnatürlich starke Kontraste, wurde durch punktuell eingesetzte Rot- und Blaulicht LEDs aufgelockert. Jeder dieser drei Lichtpfade zeigte ein anderes zeitliches Verhalten: während sich die Fasern sehr schnell im Wind bewegten, unterlag das von den Blättern reflektierte Licht zusätzlich einer zeitlich träger ablaufenden Bewegung, während die Bodenre-

flexion mehr statisch ablief. Der menschliche Betrachter mit seiner ausgeprägten Grün-Sensitivität erlebte die zeitlich-räumliche Erratik dieses Wechselspiels von Natur und Kunst sowohl fasziniert wie irritiert. Krischke gewann mit dieser Arbeit den Publikumspreis der Blauen Nacht 2014 (www.blauenacht.nuernberg.de/Archiv%202014) in Nürnberg.

B. Braunecker



Sommerplanetenkunstwiese

Anlässlich der Blauen Nacht begrünete ich die Vestertorbastei der Nürnberger Burg mit einer künstlichen Wiese. Sie war so künstlich, dass sie nicht von dieser Welt schien. Ein magisches Leuchten, das die Bäume und Bänke erfasste, spiegelte die Sehnsucht nach einem unerreichbaren Planeten, auf dem immer Sommer ist. Neongrün strahlende Halme wiegten sich im galaktischen Wind, der auch die am Boden ausgelegte Folie zum Rascheln brachte, welche das Licht zusätzlich streute. Wo keine Folie war, konnte man das Gelände begehen und sich auf Bänken niederlassen.

Petra Krischke, www.petra-krischke.de



IPT-Sélection Suisse 2016 : Compte-rendu

Le 5 décembre dernier a eu lieu la Sélection Suisse pour l'International Physicists' Tournament (IPT) édition 2016, pour déterminer quelle université représentera la suisse en avril prochain à Paris.

8h30, samedi matin. Dans les couloirs vides de l'EPFL, Lucy s'active. Membre du comité d'organisation et représentante suisse auprès du comité international de l'IPT, elle a à coeur que tout se passe pour le mieux. Cette année, la compétition internationale réunira 15 équipes. Il s'agira donc d'être à la hauteur. "L'International Physicists' Tournament se développe rapidement, et devient de plus en plus compétitif au fil des années", dit-elle. "Il nous faut donc suivre le rythme. La sélection suisse joue plusieurs rôles: tout d'abord, elle permet de sélectionner la meilleure équipe pour représenter notre pays, mais elle prépare aussi les équipes au format assez particulier de la compétition. Et pousse aussi les équipes à commencer leur préparation suffisamment tôt!"

Pour la première fois dans l'histoire de l'IPT en Suisse, deux universités différentes participent à la sélection nationale. Le tournoi en est à sa huitième édition, et la Suisse y prend part pour la 6ème année consécutive. Une belle régularité, ponctuée par deux éditions organisées à l'EPFL en 2013 et 2014. Cette année, la compétition nationale voit s'opposer une équipe de l'Université de Fribourg composée partiellement de participants de l'édition 2015 à une équipe d'étudiants de 3ème année de l'EPFL novices de la compétition. Au menu, trois des dix-sept problèmes sélectionnés pour l'édition 2016¹. Le premier problème s'intéresse au magnétisme, en demandant aux participants d'expliquer le fonctionnement d'un canon magnétique composé de plusieurs aimants fixes et de billes de métal. "Un montage basique, 2 ou 3 billes, un aimant ... simple n'est ce pas ? Et pourtant il y a bien des choses à raconter sur ce canon!", dira Ayméric. Le second problème consiste à expliquer pourquoi une chaîne composée par de petits bâtonnets de bois entrelacés (photo ci-dessous), tels ceux sur lesquels les glaces sont moulées, explose lorsque l'on retire le premier bâtonnet de la chaîne. Un problème bien plus compliqué qu'il n'en a l'air au premier abord, d'après Eric, membre de l'équipe EPFL: "Un jury nous a demandé d'expliquer le problème à un enfant, malheureusement, même des étudiants de l'EPFL ont eu du mal à le comprendre." Un avis partagé par



¹ Les problèmes de la sélection suisse, ainsi que la liste de problèmes pour l'édition 2016 se trouvent à l'adresse <http://switzerland.iptnet.info/about/>.

Benoît, de l'équipe fribourgeoise. "Au final rien ne marchait vraiment, et ça a été une grosse déception par rapport à nos attentes, que l'on a dissimulée comme on a pu." Enfin, le troisième problème fait appel aux qualités d'ingénieur des participants, en leur demandant de construire une fontaine propulsant de l'eau le plus haut possible, avec comme seule source d'énergie deux piles AA. "Avec 2 piles de 1.5 Volts et une astuce pour tuyau d'arrosage on a réussi pomper de l'eau sur 3 étages, soit près de 10 mètres!" s'exclame André. Son partenaire Benoît y voit même une certaine forme d'art: "Des fontaines, on en voit partout et il en existe de tous les types. Le jet d'eau de Genève est un très bel exemple. C'est un beau défi de réaliser ces oeuvres et c'est d'autant plus intéressant quand il s'agit d'en créer une à partir de quasiment rien."



Benoît, de l'équipe CRAABE, présente son idée d'une fontaine à eau.

Les deux équipes s'affrontent en suivant un format proche de celui de la compétition officielle: l'une des équipes choisit le problème qui devra être présenté et challenge l'équipe adverse, cette dernière ayant 10 minutes pour exposer sa solution. Une fois ce temps écoulé, l'équipe opposante se voit attribuer 5 minutes pour relever les points positifs et négatifs de la présentation de son adversaire, ainsi que différentes pistes à explorer pour améliorer le résultat final. S'ensuit alors durant un quart d'heure une discussion entre les deux équipes sur ces différents points, le but ultime étant d'arriver à un consensus sur ce qu'il faut améliorer pour obtenir une meilleure solution.

Toutes ces différentes étapes se déroulent sous les yeux des membres du jury, un panel d'experts travaillant dans différentes universités suisses et chargés de mettre une note aux différentes prestations après avoir pu poser leurs questions aux participants. Puis, les rôles s'inversent, et c'est au tour de l'équipe alors opposante de se faire challenger et de présenter sa solution au problème choisi par son adversaire. "Les 10 minutes de présentation ne sont jamais suffisantes pour tout dire et forcent les étudiants à structurer leurs idées de manière extrêmement claire, choisir ce qui est le plus important et mettre leurs idées sous le format d'une présentation limpide", indique Csaba Forro, ancien participant et désormais membre du jury. "Durant la discussion d'opposition, il faut que les participants aient réfléchi à tous les détails et subtilités du problème et aient préparé des slides

de 'back-up'. De plus, il faut être capable de mobiliser toutes ses connaissances et son bon-sens de physicien pour mener à bien un débat en général musclé, suivi des questions des membres du jury qui sont pour la plupart des physiciens de longue date difficiles à berner par un beau parleur occasionnel." Quant aux clés pour réussir au mieux, quelles sont-elles? "En assistant plusieurs fois à cette compétition, j'ai remarqué que les étudiants apprennent très vite que ce qui est récompensé est l'honnêteté intellectuelle et le débat franc, courtois, où l'on laisse la parole à l'adversaire pour s'engager dans une discussion intellectuellement extrêmement stimulante. Je suis personnellement convaincu que d'inciter à l'humilité, à l'honnêteté intellectuelle et à l'écoute attentive des idées et des objections de l'adversaire pour faire évoluer un débat de qualité est le message le plus important véhiculé par cette compétition."



Au moment d'attribuer les notes, les membres du jury semblent convaincus.

La compétition s'achève aux alentours de 12h30. Forte d'une présentation solide et d'un travail en laboratoire remarquable, l'équipe de l'EPFL prend un avantage aux points que l'équipe fribourgeoise ne pourra pas rattraper, malgré une certaine domination lors des discussions ou l'expérience emmagasinée l'année précédente s'est tout de même faite sentir.

Forte de cette victoire, l'équipe EPFL dénommée CRAABE - pour Carla, Rebeca, Aymeric, André, Benoît et Eric, s'est alors directement engagée dans l'étape suivante, une présélection au niveau international entre les différents pays inscrits au tournoi, pour déterminer lesquels feront partie des 15 équipes sélectionnées pour défendre les couleurs de leur pays à Paris. Forte d'une 3ème place dans cette épreuve, CRAABE représentera donc la Suisse en avril 2016 à Paris grâce au soutien de la Société Suisse de Physique et de SCNAT, qui prend en charge les frais d'inscription au tournoi. Face à elle se trouveront de nombreuses équipes elles aussi issues de sélections nationales française, russe, allemande ou encore ukrainienne mais aussi des équipes qui participent pour la première fois au tournoi, comme celles de l'Université de Queensland en Australie ou encore l'Université de Los Andes en Colombie. Un challenge des plus relevés qu'il s'agira de préparer avec toute la rigueur nécessaire.

Heureusement, en plus d'une grande motivation, l'équipe suisse peut compter sur le soutien de son école: pour la première année depuis ses débuts dans le tournoi, la section de physique de l'EPFL a permis à ses étudiants d'entreprendre la préparation de la sélection suisse dans le



Les membres de l'équipe CRAABE, vainqueurs de la sélection suisse 2016, prennent la pose.

cadre des Travaux Pratiques de 3ème année, et poursuivra l'expérience au semestre de printemps en vue du tournoi international. "Les étudiants avaient accès aux instruments de mesure et médias des Travaux Pratiques" indique Daniele Mari, Maître d'Enseignement et de Recherche. "Un coach animait et stimulait les discussions des étudiants en vue de la modélisation des phénomènes. L'expérience s'est révélée extrêmement intéressante du point de vue de la formation de ces futurs physiciens. En effet, les étudiants sont confrontés à des phénomènes physiques inhabituels ou curieux dont le modèle n'existe pas ou a été étudié seulement partiellement dans le passé. Ils conçoivent eux-mêmes les expériences nécessaires pour définir des paramètres significatifs et ensuite développent un modèle physique, et apprennent ainsi de manière très concrète la méthode scientifique. Cet apprentissage 'libre' constitue un excellent complément de l'apprentissage dirigé, favorisant l'autonomie, la responsabilisation et naturellement le travail en équipe."

De plus, dans un très bel exemple de collaboration entre deux institutions romandes, les membres de l'équipe de l'Université de Fribourg se sont spontanément proposés pour entraîner l'équipe de l'EPFL lors de présentations et oppositions "à blanc" en prévision de la compétition internationale. "Je propose mon aide pour la même raison qui m'a poussé à participer au tournoi : je suis curieux de connaître la solution de tous ces problèmes", dira Benoît. "Je suis authentiquement intéressé par la raison qui pousse un entrepreneur de bouts de bois à former un serpent, ou encore par le phénomène qui régit la répartition des craquelures dans le verre brisé."

Pour la 5ème fois en six participations, c'est donc l'EPFL qui représentera la Suisse à l'International Physicists' Tournament. L'historique des résultats, avec une victoire en 2013 atteste que tout est possible pour l'équipe CRAABE. Il ne fait toutefois aucun doute que les autres grandes institutions suisses seraient elles aussi capables d'aligner une équipe pouvant rivaliser avec les meilleures universités de par le monde. En 2017, qui sait ?

Vivien Bonvin, pour le comité d'organisation

PS: Le comité tient à remercier chaleureusement les membres du jury pour leur expertise, les bénévoles ayant aidé à l'organisation et au bon déroulement de l'événement ainsi que la SSP et l'EPFL pour leur soutien.

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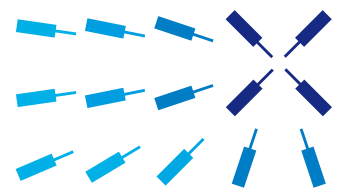
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