⟨S|P|S⟩
swiss physical society

Nr. 57
März 2019

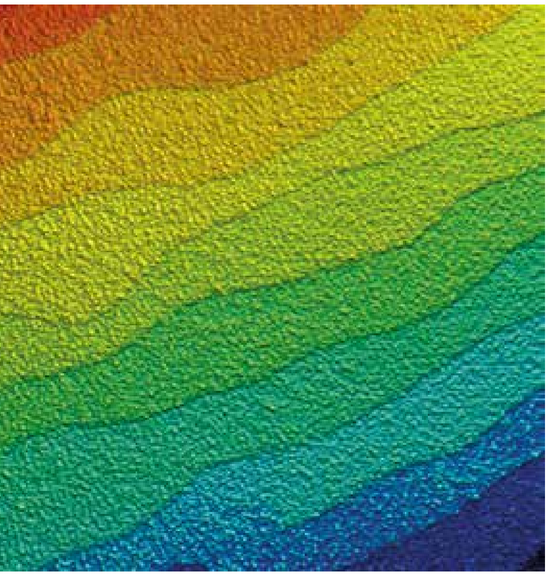
SPG MITTEILUNGEN
COMMUNICATIONS DE LA SSP

Joint Annual Meeting of the SWISS PHYSICAL SOCIETY AUSTRIAN PHYSICAL SOCIETY

26 - 30 August 2019, Universität Zürich

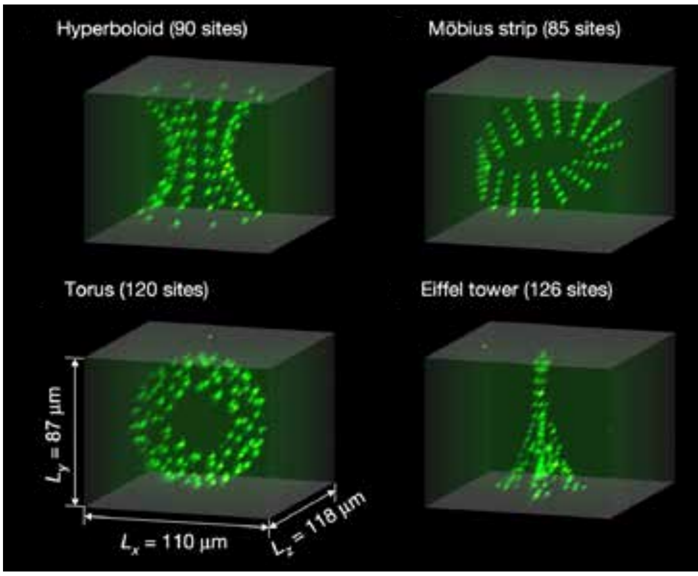
in collaboration with
ASSOCIATION MANEP, NCCR QSIT AND SGN

Call for Abstracts: Submission Deadline 30 April 2019
More information on page 5.



Left: Topography showing atomic steps of strontium titanate imaged with a Nanosurf FlexAFM (image size: 1.1 µm). Read on p. 47 an interview with Nanosurf's Head of R&D, Nikola Pascher.

Right: Optical tweezers allow to arrange individual atoms in three-dimensional patterns. Read more on p. 44.
Image: A. Browaeys.



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Die SPG Mitteilungen erscheinen ca. 2-4 mal jährlich und werden an alle Mitglieder abgegeben.

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CHF 20.- pro Jahrgang (Inland; Ausland auf Anfrage), incl. Lieferung der Hefte sofort nach Erscheinen frei Haus. Bestellungen bzw. Kündigungen jeweils zum Jahresende senden Sie bitte formlos an folgende Adresse:

Verlag und Redaktion:
Schweizerische Physikalische Gesellschaft, Klingelbergstr. 82, CH-4056 Basel, *sps@unibas.ch, www.sps.ch*

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Druck:
Werner Druck & Medien AG, Leimgrubenweg 9, 4053 Basel

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satw it’s all about technology

Editorial

Cyber-Physical Systems

Bernhard Braunecker

With this editorial we would like to draw your attention to the fact that modern industrial processes need besides engineering knowledge a *profound physical understanding*. The reasons are the increasing complexity of new technologies, but also to take full advantage of the huge application potential which they offer. The stronger focus on Physics, which would be a paradigm change in production, is indicated by the name ‘cyber-physical systems’, but more or less understood as the pure merging of production engineering with information and communication technologies ICT. We will show, however, that the experience of physicists is necessary to increase the production efficiency, whereby the key to advance are the concepts of *Digital Twins* and their physical modelling. We will further show, that these concepts also hold to run instruments and machines with much more stability.

Autonomous Modules for Industry 4.0

The complete digitalization of production systems is worldwide considered as the 4th major step of the industrial evolution and thus called ‘Industry 4.0’. It connects subsystems with each other for optimal exchange of information but also with external sources like the internet of things IoT. Modern process modules work autonomously: they are controlled by smart sensors which data are analyzed by algorithms which guide actuators like robots for different tasks. Examples are the mechanical assembling of components, the welding of metallic parts, the precise 3D-Laserprinting of tools and the tracking of fast moving objects. This closed loop concept is shown in the upper part of figure 1, where we describe the workflow through adjacent and interacting submodules as part of the ‘real or analogue’ production world.

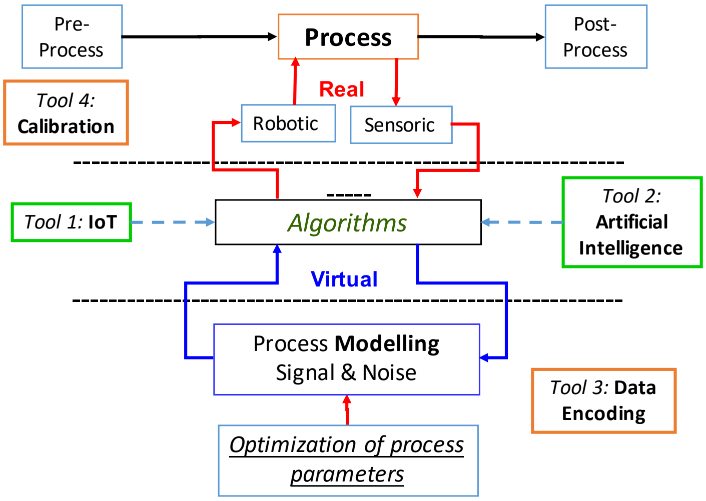


Figure 1: Real and virtual production chain.

Digital Twins of the real World

While these concepts already did significantly increase the process efficiency, further and strong improvements are expected by introducing the idea of *digital twins* or *shadows*. To this purpose each process module in the real chain is ‘mirrored’, i.e. digitally modelled, as shown in the lower part of figure 1. If performed appropriately, then the results of the total virtual chain are pseudo-measurement data, comparable with the ‘true’ measurement results. Special algorithms first have to check the consistency of the virtual data with the reality, and if verified, to vary the model parameters until a mathematical proved coincidence between real and virtual data is achieved.

Minimizing Errors

What are the advantages using a dual processing architecture? Dual concepts are well known in Physics e.g. in Fourier Transform Spectrometry, where the spectral information is first collected by an interferometer and then digitally reconstructed by fast algorithms like the FFT. The big advantage of a two-step-process is a better signal to noise ratio (SNR), i.e. that all photons are collected and no photon is wasted. The motivation for duality in industry is similar, since one wants to overcome existing physical limitations and gain more robustness against process distortions. Each module operates in an environment characterized on the one side by resolution limits like the diffraction blur of the optics or by the finite pixel size of the sensors, and on the other side by *systematic* errors like optical aberrations or de-adjustments of components, and *stochastic* errors resulting from mechanical vibrations, thermal gradients, dust contaminations, detector noise etc. They all lead to an uncertainty range of the output signals, and expensive hardware solutions are needed to keep them within the specified limits. Using, however, digital twins one could physically model the error sources, calculate their propagation through the processing modules, and find means to reduce their impact on the final results.

Data Encoding

Fourier Transform Spectrometry may again serve as method of how to proceed. Since the interferometer data are the

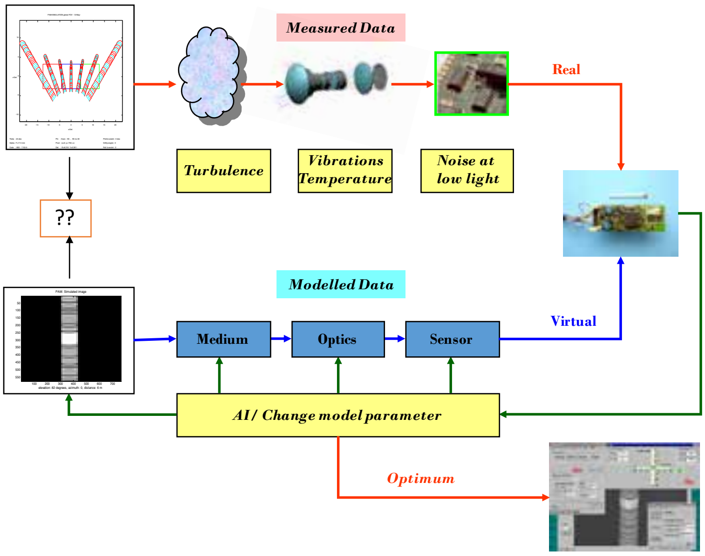


Figure 2: Stochastic Estimation of Object Position & Orientation with a barcode pattern.

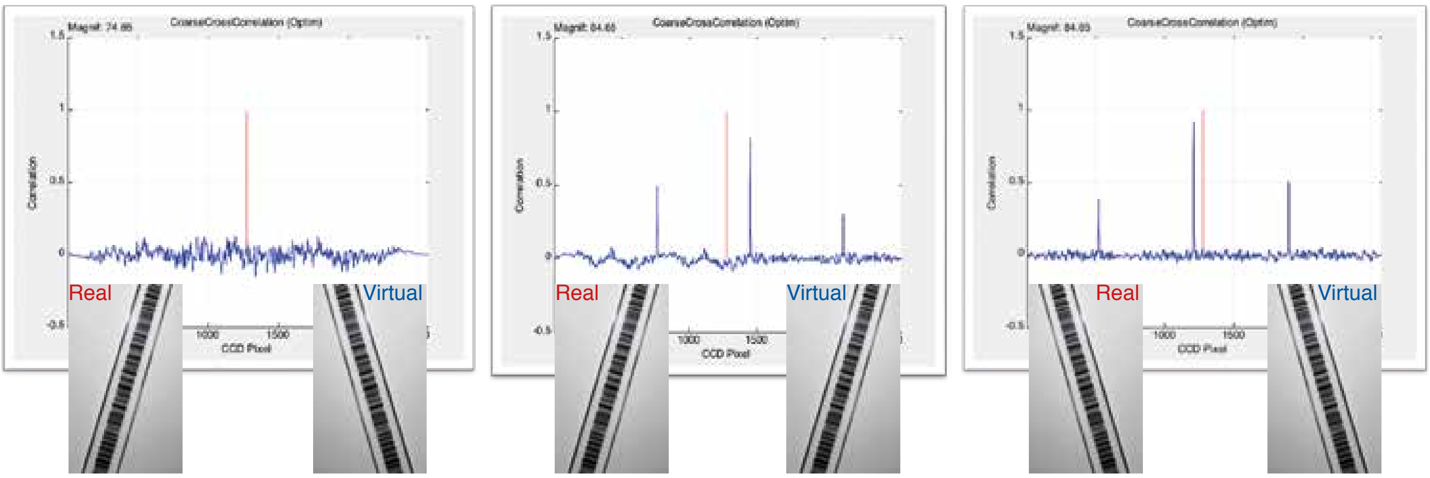


Figure 3: Crosscorrelation between real and virtual code orientation, a: no match, b,c: matched positions for different code orientations.

spectral data encoded by harmonic functions, one should also apply encoding techniques for the process parameters in the real world. An example is shown in figure 2, where a barcode on a rod is moved and rotated in space and imaged on a 2D-sensor. The barcode's six degrees of freedom DoF (3D-position and 3D-orientation) can be deduced from the code image position, -size, -rotation and -chirp. To reduce the measurement distortions caused by turbulent media, optical aberrations, finite sensor size and pixel noise, the whole chain is digitally modelled and special algorithms (maximum likelihood estimators) compare the real and virtual sensor signals. Then the barcode is virtually moved in 6D until one obtains a strong indication for a perfect match, e.g. a strong crosscorrelation peak (figure 3 a,b). Its value is further increased by fine tuning of all model parameters including the noise models and can be evaluated with high precision from the peak position on the sensor array (figure 3 b,c). The barcode method is very flexible and can be universally applied to align semiconductor wafers with sub-µm accuracy, to guide dozer and grader machines in tunnels with cm accuracy or to steer large astronomical telescopes with high angular precision in real time.

Noise Equivalence

When measuring a physical quantity Q like one or all of the six DoF under noisy conditions, then the minimum resolvable value is described by the Noise equivalent quantity NeQ, where the SNR of the measurement is 1. Using a collective like a barcode pattern as information carrier, then the NeQ depends also on the inverse of the square root of the code length and on the curvature == sharpness of the autocorrelation peak, a consequence of the randomness of the code structure. This all results in a much better measurement performance and NeQ values of about one pixel/100 rms are realistic.

Self-calibration

While the encoding reduces the stochastic errors, wrong model assumptions would introduce deterministic errors. This can be avoided first by testing prototypes in the factory and later when operating by a permanent self-calibration. This is not new, since large astronomical telescopes record besides star objects also reference or even artificial stars, earth observation satellites also look into spectral and radiometric calibration spheres, and powerful laser beams for precise material ablation also write permanently test pattern on sensors to check the correct scanning geometry.

Summary

Cyber-Physical systems combine real world processes with their digital shadows, and compare both results by algorithms. If the model assumptions are physically correct, then the whole process is less distortion sensitive and thus more reliable and accurate. Encoding of the information is a powerful tool to reduce the stochastic errors, while systematic errors are minimized by online calibration. In conclusion, physical modelling is the key for this powerful and new concept in the technical world.

Figure 4: Boston, Subway station: The barcode rod is recorded by a digital level instrument, and mechanical deformations of sub-mm amplitude are quantitatively detected.

Code Features

The code pattern must deliver a strong autocorrelation peak, even when partially contaminated by distortions, and fast encoding/decoding algorithms like the FFT must exist. Well suited are binary M-codes which are generated by algorithms and which are cyclic. Then the M-transformation of functions, i.e. their encoding, results in a convolution where the transformation coefficients are numerical values of the same order of magnitude. This is an advantage to make better use of the dynamic range of a sensor.

However, in the case of strong blurring, if e.g. the object with its barcode is far away so that the code structure is no longer resolved by the sensor pixel, the code must be designed to 'condense' into a new code with again good correlation properties. This request for a code in a code in a code is a challenge for the code designer.

Literature: E. E. Fenimore; Applied Optics Vol. 22.No. 6, 826, (1983)

Joint Annual Meeting in Zürich, 26 - 30 August 2019

The next annual meeting, again a joint one with the *Austrian Physical Society* (ÖPG), will take place from 26 - 30 August 2019 at the Universität Zürich (UZH). Renowned invited speakers will give plenary talks during each of the morning sessions, topical parallel sessions will allow in depth discussions during the afternoons, and a poster exhibition will complement the scientific program.
The scientific program is further enriched by the direct contributions of *Association MaNEP* (*Materials with Novel Electronic Properties*), the *NCCR QSIT* (*Quantum Science and Technology*) and the *Swiss Society for Neutron Science* (SGN), leading to an exciting conference, covering latest advancements of physics in a wide range of fields at its best.

Many thanks go to the Physik Institut of UZH, in particular to Prof. Johan Chang and his team, for their generous help and support with the organisation.

Scientific Program

Pre-Conference Workshops

Two workshops are organised on Monday 26 August (see p. 8):

- Machine Learning for Experimental Quantum Physics
- Programming a Quantum Computer with Examples in Quantum Machine Learning

Plenary Session

Nine plenary talks will adress latest advancements in different research fields:

- **Claudia Draxl,** Humbold-Universität Berlin:
  Artificial intelligence in materials science - hype or revolution?
- **Anna Fontcuberta i Morral,** EPFL:
  Compound semiconductor nanowires synthesis and sustainability aspects
- **Edda Gschwendtner,** CERN:
  First electron acceleration in AWAKE, the proton driven plasma wakefield acceleration experiment
- **Ravid Helled,** Universität Zürich:
  Understanding Giant Planets
- **Patrick Maletinsky,** Universität Basel:
  Probing nanoscale magnetism using single spin magnetometry
- **Greta R. Patzke,** Universität Zürich:
  Economic Materials Design for Clean Energy
- **Olaf Reimer,** Universität Innsbruck:
  Galactic High-Energy Particle Accelerators
- **Heike Riel,** IBM Rüschlikon:
  The Future of Computing
- **Monika Ritsch-Marte,** Med. Universität Innsbruck
  Synthetic holography with spatial light modulators for biophotonics applications

Furthermore a public lecture is scheduled in the evening of Tuesday 27 August:

- **Rainer Blatt,** Universität Innsbruck
  The Quantum Way of Doing Computations (New Technologies for the Information Age)

Topical Sessions

The following parallel sessions will be scheduled from Tuesday to Friday:

- Applied Physics and Plasma Physics
- Atomic Physics and Quantum Photonics
- Biophysics, Medical Physics and Soft Matter
- Condensed Matter Physics
- Earth, Atmosphere and Environmental Physics
- History and Philosophy of Physics
- MaNEP: Correlations and topology in quantum matter *
- Nuclear, Particle- & Astrophysics
- Quantum and Artificial Intelligence: New Jobs for Physicists in Emergent Industries
- Quantum Beam Science: bio, materials and fundamental physics with neutrons and X-rays ***
- Quantum Science and Technology **
- Surfaces, Interfaces and Thin Films
- Skyrmions in magnetic materials *

* organised in collaboration with Association MaNEP, ** organized in collaboration with NCCR QSIT, *** organized in collaboration with the Swiss Society for Neutron Science (SGN)

Dependent on the number and contents of the contributed papers, each topical session can be split into special thematic subsessions.

Poster Session

The poster session will start on 28 August evening with an apéro and will continue on 29 August with a lunch buffet.
It is expected that **all** posters are presented on both session days.

The three most outstanding posters will be awarded with a "Best Poster Prize". It is required that at least the first author of the poster is personally present at the conference in order to be eligible for the award.

The maximum poster size is A0 (portrait).

Award Ceremony

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

ÖPG, CHIPP and the Swiss Society for Neutron Science will also award their respective winners.

The award ceremony will be held on 28 August at 10:50h.

General Assembly

The general assembly is scheduled for 27 August 2019 in the morning. The agenda will be published in the next issue of the *SPG Mitteilungen*. We encourage all members to actively participate and contact the committee if special points of interest should be discussed at the assembly.

Conference Dinner

A conference dinner is scheduled for the evening of 29 August. Information on the location, price and more details will be available on our web site soon.

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 invitation letter, please contact: *sps@unibas.ch*

Abstract Submission:
Deadline 30 April 2019

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, and 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 submission form will be activated in mid-March.
The conference program will be available in June 2019 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 (Wednesday) and lunch buffet (Thursday).
The conference dinner on Thursday 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, 2019.

Category:	*CHF*
Members of SPS, ÖPG	140.-
Ph.D. Students who are members (*)	100.-
Ph.D. Students who are not members (*)	140.-
Students before Master/Diploma degree (*)	80.-
Plenary speakers, invited speakers, awardees	0.-
Other persons	180.-
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 2019

Special offer for non-members:

Do you plan to participate in our meeting and want to become a member of SPS ? Then take advandage of our special offer of CHF 190.- covering the conference fees and the membership for 2019. (CHF 210.- 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.)

Hotel Reservations

We have reserved a contingent of rooms for our participants in various hotels. Detailed information, as well as the booking options, will be available directly on the conference registration website.

SPS swiss physical society

Österreichische Physikalische Gesellschaft

MaNEP SWITZERLAND

QSIT Quantum Science and Technology
National Centre of Competence in Research

Universität Zürich UZH

Additional information for selected sessions

Theoretical Physics

Theoretical contributions are highly encouraged and will be included directly in a corresponding topical session. This way, the sessions will profit from a broad range of experimental, phenomenological, and theoretical advancements that are relevant in the specific topical field and thus can engage in broader and deeper discussions.
Please submit your abstract to the session which best matches your topic. You can optionally mark your contribution as "theoretical" in the submission interface.

Contact: Philippe Jetzer (jetzer@physik.uzh.ch)

Quantum and Artificial Intelligence: New Jobs for Physicists in Emergent Industries

In recent years, quantum technologies and artificial intelligence have started to impact an amazingly wide range of fields, from research instrumentation to financial modelling. Beyond the research domain, more and more products are being made with or for these new technologies. In this session, opportunities for physicists in these emergent industries will be presented. If you have an interesting story to tell on this subject, please submit your contribution before the abstract submission deadline.

Contact: Thilo Stöferle (tof@zurich.ibm.com)

Quantum Science and Technology *(organized by the NCCR QSIT)*

The quantum science and technology session will combine presentations on recent scientific advances in the fields of quantum computing, communication, simulation and sensing. Both Austria and Switzerland are important players in the quantum technology landscape in Europe with many groups contributing to the European Quantum Flagship and other important international research programs. The session is organized by the Swiss National Center of Competence in Research on Quantum Science and Technology and wishes to bring together the two quantum communities from Austria and Switzerland. We welcome oral and poster contributions from both senior and junior researchers. Please submit your contribution before the abstract submission deadline.

Contact: Andreas Fuhrer (afu@zurich.ibm.com)

Condensed Matter (KOND)

The condensed matter program welcomes contributions from all topics within Condensed Matter Physics, including magnetism, superconductivity, semiconductors and more.
Where relevant, we encourage participants to submit their abstracts to the relevant focus sessions described below.

Contact: Henrik M. Rønnow (henrik.ronnow@epfl.ch), Alberta Bonanni, (alberta.bonanni@jku.at)

Quantum Beam Science: bio, materials and fundamental physics with neutrons and X-rays

The Swiss Neutron Science Society, the PSI division for photon science and their Austrian counterparts invite abstracts from the growing user-base of neutron, synchrotron and free electron laser facilities to share their research. Abstract submissions are welcome from all topics where neutron or X-ray experiments have contributed. Contributions do not have to be centered on the technique and we specifically encourage contributions where quantum beam experiments were one among several techniques involved.

Contact: Neutrons: Markus Strobl (markus.strobl@psi.ch), X-rays: Luc Patthey (luc.patthey@psi.ch), General: Henrik M. Rønnow (henrik.ronnow@epfl.ch)

MaNEP Session: Correlations and topology in quantum matter

The session is dedicated to recent developments in the study of materials with novel electronic phenomena that arise from electronic correlations or topological properties. This encompasses the physics of low-dimensional materials including van der Waals materials and surface or interface physics, quantum magnetism, superconductivity, the physics of oxide materials, topological phases of matter, novel probes and more. Abstract submissions are welcome from all researchers working in the field, you don't have to belong to a MaNEP member group.

Contact: Marta Gibert (gibert@physik.uzh.ch), Titus Neupert (titus.neupert@uzh.ch)

MaNEP Focus Session: Skyrmions in magnetic materials

Over the last decade, there has been a huge research effort into skyrmions stabilized in magnetic materials. Due to their nanometric size, topological protection and easy manipulation by external stimuli, skyrmions offer new perspectives for spintronics and cutting-edge device technologies. Within the framework of a running Swiss National Science Foundation (SNSF) funded Sinergia project 171003 'NanoSkyrmionics', in this focus session we bring together experimentalists and theoreticians from both Switzerland and abroad, to highlight recent advances in materials discovery, measurement and control of skyrmions. Xiuzhen Yu (RIKEN CEMS, Japan), Peter Hatton (Durham University, UK), and Stefan Blügel (FZ Jülich, Germany) will give invited talks. Abstract submissions are welcome from all researchers working in the field, you don't have to belong to a MaNEP member group. Financial support from both MaNEP and the SNSF is gratefully acknowledged.

Contact: Jonathan White (jonathan.white@psi.ch)

Pre-Conference Workshops, Monday 26 August 2019

These workshops will consist of a morning part with introductory lectures followed by two tutorial sessions in the afternoon. The morning lectures are intended for participants of both workshops. However, the afternoon parts will run in parallel so you can choose only one of the two events upon registration (limited number of participants).

WS 1: Machine Learning for Experimental Quantum Physics

This one-day workshop introduces the principles of neural-network-based machine-learning applications in condensed matter, quantum mesoscopic physics, and quantum optics. In two lectures, the theoretical background of supervised learning with deep neural networks will be discussed, including convolutional networks, various regularization schemes, and an overview on existing applications. In a tutorial session elementary examples are demonstrated step-by-step and the participants will learn how to set up a simple neural network calculation using the Keras environment in Tensor Flow. The topics are geared towards experimental data analysis. The goal of the workshop is to enable participants to use elementary machine-learning techniques in their research. No previous knowledge is required, except for elementary command of python in the hands-on programming session at the end of the workshop. To participate in the hands-on session, a laptop with internet connection is needed.

Contact: Titus Neupert (neupert@physik.uzh.ch)
Further lecturers / tutors: Mark Fischer (Uni Zürich), Eliska Greplova (ETHZ), Kenny Choo (Uni Zürich), Frank Schindler (Uni Zürich)

WS 2: Programming a Quantum Computer with Examples in Quantum Machine Learning

In this workshop we first provide a general introduction followed by a hands-on experience on how to program quantum computers with Qiskit. We show how to implement quantum circuits in Python, how to simulate them using classical computers, and how to run them on real quantum hardware via the IBM Q Experience. Based on this fundament, a quantum machine learning algorithm for classification is introduced and it is shown how to train and test it for any given dataset. To participate in this workshop basic knowledge of how to program in Python is required and a laptop with an internet connection. Ideally, you have already installed Qiskit and Qiskit Aqua (pip install qiskit / pip install qiskit_aqua).

Contact: Stefan Woerner (wor@zurich.ibm.com)
Further lecturer / tutor: Christa Zoufal (IBM Research – Zurich)

References:

http://qiskit.org
http://learnqiskit.org/
https://nbviewer.jupyter.org/github/Qiskit/qiskit-tutorial/blob/master/index.ipynb

EPS Historic Site 2019

The ***High Altitude Research Station Jungfraujoch HFSJG*** (*https://www.hfsjg.ch/en/home/*) received the prestigious award as "EPS Historic Site" from the European Physical Society. This is the fifth recognition of Switzerland as a significant place for the development of modern physics after the Synchro-Cyclotron at Cern (2014), the Einstein Haus in Bern (2015), “Les Bastions” of the University of Geneva (2017) and the IBM Research Laboratory in Rüschlikon (2017). Switzerland takes the second place behind Italy with six awards.

The award ceremony took place in two steps, first with a half day symposium at the University of Bern on February 7th, followed by an excursion to the Jungfraujoch the day after, where the plaque was unveiled by EPS President Rüdiger Voss (left picture, right) and the president of HFSJG foundation Silvio Decurtins (left). It is obvious that the plaque at a height of 3454 m belongs besides the Laboratory "Les Cosmiques" at Col du Midi in Chamonix to the 'highest' EPS awards.

About 30 scientists joined the ceremony and enjoyed the wonderful scenery at best weather conditions. The SPS president, vice-president and secretary followed the invitation and were deeply impressed by the relevance of the experiments for meteorology, climatology, solar and stellar astronomy.

In Memoriam Gustav Andreas Tammann

Gustav Andreas Tammann, a prominent scientist, renowned for his fundamental contributions to research in extragalactic astronomy and cosmology, died on 6 January 2019 in Basel, at the age of 86.

He was born in Göttingen on 24 July 1932 as son of the medical professor Heinrich Tammann and his wife Verena (née Bertholet). His paternal grandfather, the chemistry professor Gustav Heinrich Tammann, initially at the University of Dorpat (today's Tartu) before moving to Göttingen, originated from the Baltic; his maternal grandfather Alfred Bertholet was theology professor in Basel. Gustav Andreas Tammann spent his childhood in Göttingen and Hannover, and in Pomerania and Bavaria during the Second World War. After the death of his father in 1946 his mother returned to her native Basel with him and his two sisters.

G. A. Tammann studied in Basel, Freiburg im Breisgau, and Göttingen. After his graduate studies in Basel he moved to the Mount Wilson and Palomar Observatories in Southern California, before taking up a position as Professor in Hamburg in 1972. Between 1977 and 2002 he was full professor and Head of the Institute of Astronomy at the University of Basel. Throughout his career he was frequently invited as visiting scientist at leading astronomical institutions, for example the Institute of Astronomy in Cambridge, and repeatedly the Carnegie Observatories in Pasadena. He continued his research as emeritus professor for another decade.

His collaboration with Allan Sandage in Pasadena, student and successor of Edwin Hubble, began in 1963. It focused on investigating the expansion of the Universe and the determination of the so-called Hubble constant H_0. This research project spanned over 20 years and resulted in an impressive series of publications on the so-called "distance ladder", from measuring distances to close stellar clusters up to those enabling the determination of the universal cosmic expansion. The results were based on observations of variable stars (Cepheids) and supernovae in far-away galaxies, as well as galaxy distributions.

In the 1980s and 1990s the value of the Hubble constant was heavily contested between two schools (Sandage and Tammann and the group around Gérard de Vaucouleurs), which had independently determined values of 50 - 60 and 80 - 100 km s^{-1} Mpc^{-1}, respectively. The public debate between Tammann and John Huchra at the 18th Texas Symposium on Relativistic Astrophysics and Cosmology in Chicago in December 1996 remains a vivid memory.

In their publication from 2008 Tammann, Sandage and Reindl obtained a value of (62.3 ± 1.3) km s^{-1} Mpc^{-1} for H_0. Tammann and Reindl's last publication in 2013 cited a value of (64.3 ± 3.6) km s^{-1} Mpc^{-1}. Even today the value of H_0 is not fully settled, possibly due to an underestimation of systematic errors. Whereas the latest determination through the distance ladder method by other groups yields (73.2 ± 1.7) km s^{-1} Mpc^{-1} (targeting the nearby Universe), the most recent value derived from the measurements of the Planck satellite, based on observations of the cosmic microwave background, is (67.4 ± 0.5) km s^{-1} Mpc^{-1}. Tammann was a pioneer in utilising supernovae to measure cosmic distances. In visionary publications he predicted their use for cosmology. At present, supernovae are indeed universally employed as the essential ultimate stepping stone of the cosmic distance ladder. With his colleagues he prepared the path toward the discovery of the accelerated expansion of the Universe and enabled the research of the *Supernova Cosmology Project* and of the *High-Z Supernova Search Team* that culminated in the 2011 Nobel Prize in Physics awarded to Saul Perlmutter, Brian Schmidt and Adam Riess.

Two books, "A Revised Shapley-Ames Catalog of Bright Galaxies" (with Sandage) and "Halley's Comet" (with Philippe Véron), as well as his more than 200 scientific publications led to distinctions such as the 'Karl-Schwarzschild Medaille', the 'Einstein Medaille', and the 'Tomalla Preis', to the membership in the Academia Europaea, the Leopoldina, the New York, Austrian and Heidelberg Academies of Sciences as well as the Academy of Naples, that underlined the proficiency of astronomy in Basel. He further contributed his expertise and advice in fulfilling many functions, namely as President of the Commission on Galaxies of the International Astronomical Union and of the 'Astronomische Gesellschaft', as member of the Space Telescope Advisory Team of the European Space Agency ESA and of the Council of the European Southern Observatory ESO, as President of the Foundation High Altitude Research Stations Jungfraujoch and Gornergrat and of the Scientific Advisory Committee of the Bernoulli-Edition, and as member of the 'Euler-Kommission' of the Swiss Academy of Sciences (then still called 'Schweizerische Naturforschende Gesellschaft'). With his standing and influence he was instrumental to the decision that Switzerland joined ESO, and moreover to the founding of the International Space Science Institute (ISSI) in Bern.

Tammann was also known to the general public through numerous public lectures, radio broadcasts, and his appearance in movies and on television. Highly impressive was when he compared the expansion of the Universe and the rising distances between galaxies with the growing distances between raisins during the baking of a yeast-based

Gugelhupf cake. His enthusiasm, his generous character and noble demeanour, his acumen and esprit won over whoever had met him.

Encounters with him and his charming wife, Yvetta Tammann-Jundt (who passed away before him and whose family history included emigration to wine-growing areas in Bessarabia on the Black Sea as well as the return to Switzerland after the Second World War) were always life-enhancing. Besides his work in astronomy that determined his professional life, he followed up genealogical subjects and built a collection of decorations and medals from around the world (*tammann.ch*). He is survived by his children Tatjana and Thomas and by five grandchildren. His students, his colleagues here and abroad will sorely miss this endearing fellow human being.

For his contemporaries, students, and former Basel colleagues:
Iris Zschokke (Basel), Martin Huber (Zürich), Johannes Geiss (Bern); Bruno Binggeli (Basel), Alfred Gautschy (Zürich), Helmut Jerjen (Canberra), Renée Kraan-Korteweg (Cape Town), Bruno Leibundgut (Garching), Anja Schröder (Cape Town); Roland Buser (Basel), Ortwin Gerhard (Garching), Eva Grebel (Heidelberg), and Friedrich Thielemann (Basel and Darmstadt).

Picture: © Hochalpine Forschungsstationen Jungfraujoch und Gornergrat

A Particle Physics Roadmap

Hans Peter Beck

Successful Standard Model

The discovery of the Higgs boson in 2012 at CERN's Large Hadron Collider (LHC) triumphally confirmed the Standard Model of particle physics, describing matter particles and their interactions. Six quarks (up, down, charm, strange, top, bottom), six leptons (electron, electron-neutrino, muon, muon-neutrino, tau, tau-neutrino), four vector bosons (photon, W-boson, Z-boson, gluon), and one scalar boson (Higgs-boson), perfectly formulated in a relativistic quantum-field theoretical framework, based on elementary symmetries $U(1)\times SU(2)_L\times SU(3)_C$ neatly explain all measurements ever made and at all accessible scales – except gravity.

Open Questions

Still, major unknowns remain and deep questions regarding the inner working of the Universe remain. Neutrino types can oscillate one into another, implying small non-vanishing neutrino masses. Probably the only but deeply vexing deviation of the Standard Model. Cosmology tells us that the major mass-energy content in the Universe cannot be explained by the Standard Model particles. Dark Matter and Dark Energy constitute 95% of the total mass-energy content, and Dark Matter constitutes 85% of the total mass content. Furthermore, according to the Standard Model, matter and antimatter was created in equal amounts at the Big Bang, although no antimatter abundancies are existing anywhere in the visible Universe. It is more than obvious that the Standard Model is not the end of the physical understanding and that it needs to be enlarged. Theoretical advances have so far failed to compellingly tell forward how the Standard Model could be enlarged or replaced. New high-precision measurements at low and at highest energies will state the only clues achievable on how to expand beyond our current horizon of understanding.

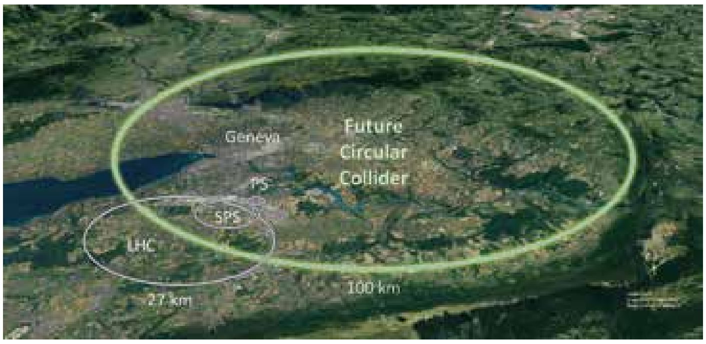
European Strategy for Particle Physics

The question on how to move forward, which experimental facilities will be best suited, and how to profit best from current existing infrastructure is a tricky one. Especially given the complexity and the long time-scales involved in experimental particle physics. For this, the European Strategy for Particle Physics group has been initiated already in 2006 to coordinate activities and to define the mid- and long-term priorities at ca. five years intervals. The next of this series of strategy update reports is due by mid 2020 [1] and input received from an open call by the European Particle Physics Strategy Update group is being reviewed and digested throughout the course of this year, taking also into account the global landscape, not limiting itself to a European view alone.

New Machines

In that context, CERN proposed its input: LHC shall be fully exploited until 2037 for which the proton-proton collision rate shall be further increased with the high-luminosity LHC (HL-LHC) upgrade. A new accelerator should be built and used after termination of the LHC program, which would define CERN's experimental particle physics program until the end of the century. Among other proposals, a 100 km circular collider, the FCC, is promising, and would also be favoured by the Swiss particle physicists [2,3], and as is also reported by the Neue Zürcher Zeitung [4].

[1] *http://europeanstrategyupdate.web.cern.ch*
[2] *https://naturalsciences.ch/topics/particlephysics/109730-the-fcc-provides-science-for-almost-a-century*
[3] *https://naturalsciences.ch/organisations/chipp/meetings_documentation/109069-swiss-input-for-the-discussion-on-the-european-strategy-for-particle-physics*
[4] *https://www.nzz.ch/wissenschaft/cern-fcc-oder-clic-was-kommt-nach-dem-lhc-ld.1454325*



Aerial view showing the current ring of the LHC (27 km) and the proposed new 100 km tunnel that could host different colliders modes (FCC-ee, FCC-hh, FCC-he). Picture: © CERN

Progress in Physics (66)

The attosecond science of solids

Lukas Gallmann and Ursula Keller, ETH Zürich

1. Introduction

The field of experimental attosecond science started in 2001 with the first successful characterization of attosecond extreme ultraviolet (XUV) bursts of radiation by two independent teams [1, 2]. Attosecond science is a sub-domain of ultrafast science that uses short laser pulses to time-resolve some of the fastest processes in nature. Given that the lightest and fastest nuclei vibrate with a 8 fs period in ground-state molecular hydrogen, it becomes evident that nuclear motion is essentially frozen on attosecond time scales. As a result, one may ask what kind of attosecond dynamics remains to be observed in this case? It is the motion of electrons, the lightest constituents of matter, that unfolds in this domain.

Due to the technical complexity of attosecond experiments, early studies concentrated on gas phase systems and, in particular, on rare gas atoms. These experiments helped to improve our understanding of the dynamics of light-induced ionization processes, ranging from single-photon ionization to tunnel ionization. In recent years, the field expanded to molecules, the liquid phase and solids.

Similar to the insights ever improving microscopy tools yielded on the structure of matter, attosecond science provides a close-up view of ultrafast dynamics in the time domain. Processes that can be approximated as instantaneous in other regimes have to be revisited and theoretical models have to be refined accordingly. New questions can be asked that were previously inaccessible to experimental studies. How long does it take for an electron to tunnel through a classically forbidden barrier? How long does it take to photoemit an electron from an atom, molecule or solid surface? How do the electrons in a solid transiently respond to an ultrafast – potentially THz to PHz – modulation through an applied electric field? While the former questions are of a fundamental nature, the latter also has direct consequences for the ultimate limits to electronic device performance.

In the following, we will review the state of attosecond science of solid systems. We illustrate its capabilities based on our recent work on optical-field-driven electron dynamics in dielectrics. Before presenting our overview and findings, we provide a brief introduction of the tools and techniques used in this type of research.

2. Attosecond light pulses

In order to perform optical time-resolved spectroscopy with attosecond resolution, one needs to generate attosecond light pulses. This is done starting from an amplified femtosecond pulse in the infrared. In the most common implementation, this pulse is focused into a rare-gas jet inside a vacuum chamber. With a focused laser peak intensity on the order of 10^{14} W/cm^2, the electric field component of the electromagnetic wave forming the infrared pulse reaches a peak field strength that becomes comparable to the inner-atomic binding forces. As a result, the laser can strong-field ion-

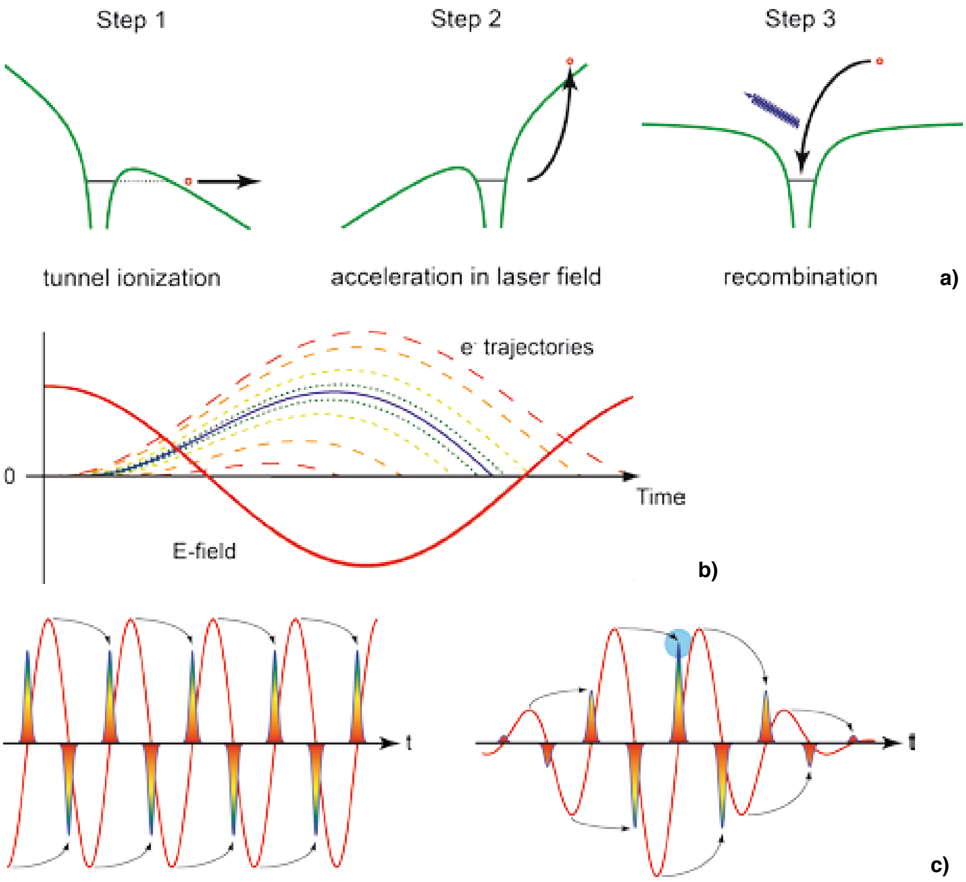


Figure 1: Attosecond pulse generation.
a) Three-step model of high-harmonic generation. The laser field tunnel-ionizes an atom by deforming its Coulomb potential (green lines). The liberated electron is then accelerated in the electric field of the laser pulse and with a certain probability recombines with the parent ion. Excess energy is emitted as a high-energy photon upon recombination.
b) Classical electron trajectories in oscillating laser field (solid red line). Only trajectories emerging within a quarter-cycle with decreasing amplitude return the parent ion (positioned on the horizontal axis). The color code of the trajectories encodes recollision energies (blue: high energy, red: low energy).
c) The process illustrated in a) and b) repeats for each half-cycle of the oscillating electric field. The arrows indicate the attosecond pulses that are emitted by recombination of electrons ionized around their origin. For a few-cycle pulse (right), the highest photon energies (marked by blue circle) are only generated for the electrons accelerated by the strongest half-cycle. High-pass filtering can therefore suppress all other attosecond pulses generated within this pulse.

ize the atoms. The liberated electrons are still exposed to the oscillatory electric field of the optical pulse. As the electric-field vector changes its direction with the optical oscillation, the electron can be accelerated back towards its parent ion, where it may recombine with a certain probability. Upon recombination, the excess energy gained by the electron during the acceleration cycle is emitted as a high-energy photon. This entire three-step process is known as high-order harmonic generation (HHG), which is also schematically illustrated in Figure 1a) [3-6]. For a pulse consisting of many field oscillation cycles, the process repeats for each sufficiently intense oscillation-half-cycle. As a consequence of this periodicity, the emitted radiation is found only at odd-order multiples of the initial infrared frequency. These harmonics can reach to very high orders due to the non-perturbative nature of this mechanism. A near-infrared driving laser centered at a wavelength of 800 nm (1.55 eV photon energy) will easily produce HHG radiation up to 80 eV (16 nm wavelength) or more. At first sight counterintuitively, a longer-wavelength driving laser can produce even higher energy photons at similar peak intensity, with record results reaching well beyond 1 keV [7]. The reason for this lies in the longer acceleration phase an electron experiences in a more slowly oscillating field.

The high-harmonic radiation is emitted in a coherent laser-like beam. The temporal structure of the emitted light is intrinsically attosecond. This can be intuitively understood when looking at the classical electron trajectories in the oscillating laser field. Only trajectories emerging during the falling quarter-cycle will actually return to the parent ion (Fig. 1b). Trajectories starting at other instances lead away from the ion. At 800 nm a full field oscillation cycle lasts 2.7 fs. A confinement of the emission to a quarter-cycle therefore already results in a sub-femtosecond pulse. The exponential field-strength dependence of the ionization probability leads to a further temporal confinement [8]. The shortest pulses to date have been measured at ETH Zürich and had a duration of 43 as [9].

If the driving infrared pulse consists of many comparably intense oscillation cycles, then a burst of attosecond pulses with half-infrared-cycle periodicity is generated. This burst is referred to as an attosecond pulse train (APT) [2] (Fig. 1c). If the HHG process is driven by a few-cycle pulse, however, the highest photon energies are produced only during the most intense half-cycle. With appropriate high-pass filtering and control of the relative phase between pulse envelope and carrier wave [10], a single attosecond pulse can be isolated [1] (Fig. 1c). An isolated attosecond pulse (IAP) has a continuous spectral power density, whereas an APT is formed by discrete harmonic peaks in the spectral domain. Both regimes are used in attosecond experiments.

3. Attosecond spectroscopy

The next ingredient to an attosecond experiment is a measurement technique that can exploit the short pulses generated through the above process to yield the desired temporal resolution. For their temporal resolution, ultrafast spectroscopic techniques typically rely on at least a pair of ultrashort optical pulses. One pulse (the so-called ‘pump’) initiates the dynamics one wants to measure, while a second pulse (the ‘probe’) probes the evolving system as a function of relative delay between the two pulses. For the probe pulse to be able to interrogate the dynamics started by the pump, the two pulses need to couple through an optical nonlinearity. In linear optics, the two pulses would just superimpose with no way for the probe to time-gate the response to the pump.

The need for an optical nonlinearity represents a particular challenge at the extreme ultraviolet (XUV) photon energies of the attosecond pulses. In general, optical nonlinearities are found to be small in that region of the electromagnetic spectrum compared to the visible or infrared domain. At the same time, the intensity of the attosecond pulses is comparably low because of the inefficient HHG process. As a consequence, most attosecond experiments rely on a two-color configuration where one of the two pulses is an intense infrared pulse with femtosecond duration while the other is the rather weak attosecond pulse. Which of the two assumes the role of the pump and which one is the probe depends on the specific experiment.

Attosecond spectroscopic techniques either record electron or optical spectra. In the former case, the energetic XUV photons of the attosecond pulse ionize a target. The resulting photoelectrons interact with the intense infrared probe. In the attosecond streak camera, the photoelectrons are accelerated or decelerated by the electric field of the infrared [1]. The final electron energy depends on the timing of the ionization event with respect to the probe. Compared to the field-free case, the electron energy is shifted up or down by the vector potential of the infrared pulse at the time of ionization (Fig. 2a). The electron spectra measured as a function of pump-probe delay correspond to the cross-correlation of the electron wavepacket created by the XUV pulse and the infrared vector potential. If transition matrix elements can be considered constant across the XUV spectrum, the electron wavepacket is essentially an energy-shifted replica of the XUV pulse. The attosecond resolution is maintained in this experiment despite the femtosecond duration of the probe because the measurement process is sensitive to the infrared field oscillations that show considerable variation on sub-femtosecond scales.

Using the same setup of the attosecond streak camera with attosecond pulse trains leads to a somewhat different result. If the infrared probe is derived from the same laser driving the HHG process, then the APT is formed by harmonics separated by twice the infrared photon energy (because only odd-order harmonics are generated). Photoelectrons created by the APT adopt its energetic structure. When interacting with the infrared probe, the photoelectrons created from a given harmonic can now absorb or emit an additional infrared photon. This brings the electron energy right in the middle between two adjacent harmonics. Because this final energy can be reached through the lower harmonic and absorption of an infrared photon as well as through the higher harmonic and emission of an infrared photon, interference between these two quantum mechanical pathways will occur (Fig. 2b). The interference on these so-called sidebands between the original harmonics modulates as a function of pump-probe delay. This method is referred to as reconstruction of attosecond beating by interference of two-photon transitions (RABBITT, [2, 11]).

How does one use the attosecond streak camera or RABBITT to resolve, for example, the attosecond dynamics of ionization processes? We can do so by performing measurements on either different ionization pathways of the same

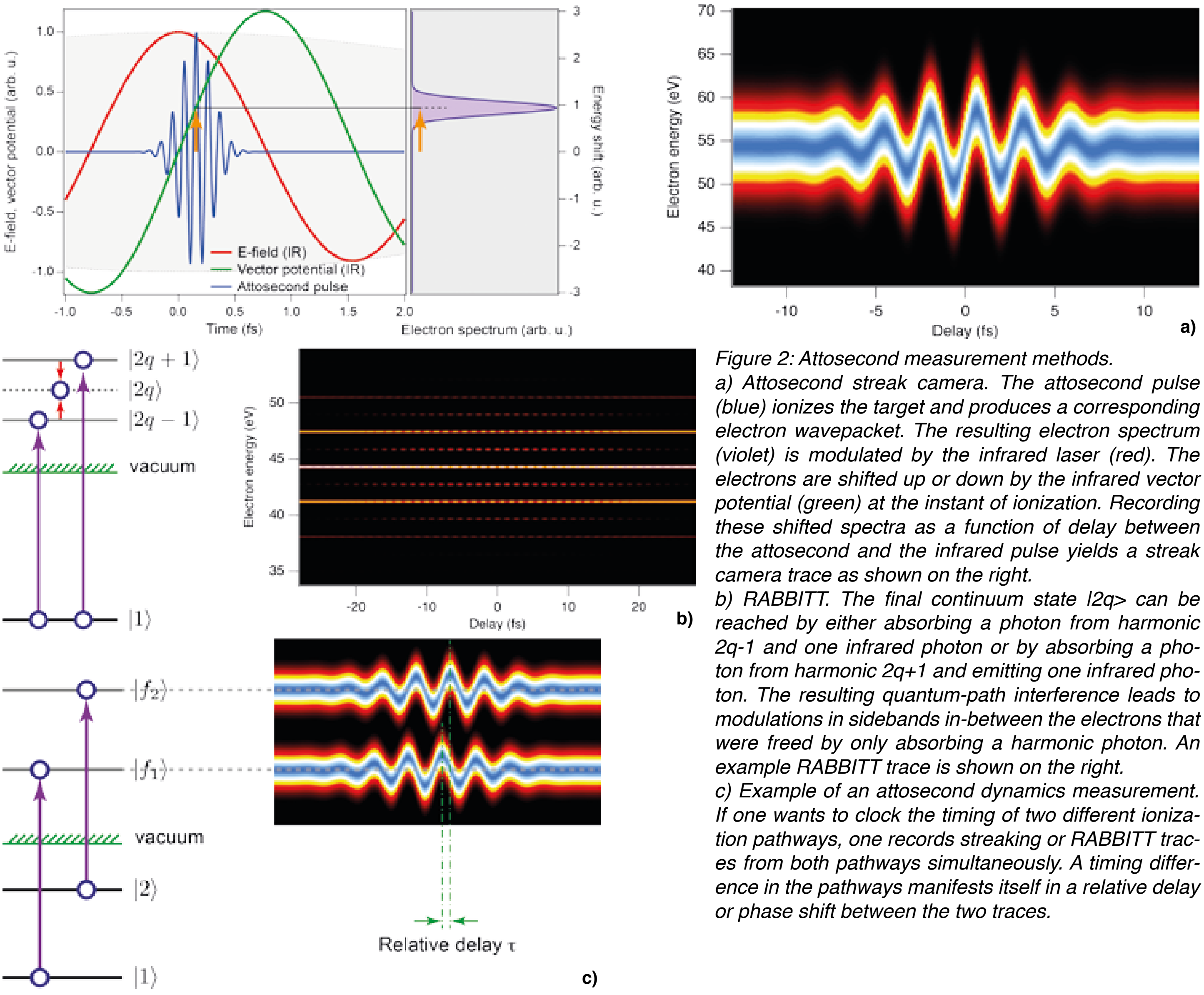


Figure 2: Attosecond measurement methods.
a) Attosecond streak camera. The attosecond pulse (blue) ionizes the target and produces a corresponding electron wavepacket. The resulting electron spectrum (violet) is modulated by the infrared laser (red). The electrons are shifted up or down by the infrared vector potential (green) at the instant of ionization. Recording these shifted spectra as a function of delay between the attosecond and the infrared pulse yields a streak camera trace as shown on the right.
b) RABBITT. The final continuum state l2q> can be reached by either absorbing a photon from harmonic 2q-1 and one infrared photon or by absorbing a photon from harmonic 2q+1 and emitting one infrared photon. The resulting quantum-path interference leads to modulations in sidebands in-between the electrons that were freed by only absorbing a harmonic photon. An example RABBITT trace is shown on the right.
c) Example of an attosecond dynamics measurement. If one wants to clock the timing of two different ionization pathways, one records streaking or RABBITT traces from both pathways simultaneously. A timing difference in the pathways manifests itself in a relative delay or phase shift between the two traces.

system (e.g. from two different initial states) or on different systems (e.g. ionization from the ground state of two different atomic species). If ionization happens more slowly in one case than in the other, the respective timing difference will manifest itself as a delay or phase shift between the data sets from the two pathways or systems (Fig. 2c). If the measurement is taken against a known reference, then the absolute timing of the ionization dynamics can be extracted [12]. A known reference can be a simple atomic system for which the ionization dynamics can be obtained with reasonable accuracy from theory. A more detailed analysis shows that the attosecond streak camera and RABBITT data provide within sampling constraints the full energy-dependent phase of the electron wavepacket created in the ionization event. This phase encodes the dynamics of the process.

Another important spectroscopic technique besides the electron-detecting streak camera and RABBITT is the all-optical attosecond transient absorption spectroscopy (ATAS, [13-15]). In this case, the infrared beam serves as a pump and initiates electron dynamics. The attosecond pulse probes these dynamics through resulting changes in the optical properties of the samples: either an increase or decrease of optical absorption. For this purpose, the optical spectrum of the transmitted attosecond pulse is recorded with and without the presence of the pump and as a function of pump-probe delay. The measurement in the absence of the pump yields the static reference for the optical properties of the sample if the process being studied has not been initiated. Any change in probe transmission observed when the pump is present must then be due to the induced dynamics. The actual dynamics is then observed by monitoring how the induced absorption change evolves as a function of pump-probe delay. If, for example, the pumped process transfers population that fills the final state of the probe transition, one would observe an increased probe transmission as fewer vacancies remain that can be populated by the probe. As the transferred population decays, vacancies become available again at sufficiently large delay of the probe to the pump. Transient absorption spectroscopy is a classical, well-established technique in the femtosecond domain and has been transferred to attosecond experiments around 2010 [13-15].

It should be noted that attosecond spectroscopic techniques can measure either electron or photon spectra with high energy resolution while maintaining attosecond pump-probe delay steps. An often found misconception is that this simultaneous high resolution in delay and energy is in conflict with the time-energy uncertainty. It is important to realize that we measure the spectra with a time-integrating detector as a function of relative delay between the pump and probe pulses rather than as a function of real time. A single delay scan is therefore composed of individual measurements from many separate laser shots. Delay and energy are not conjugate quantities and therefore no uncertainty limitation applies in this case. The energy uncertainty arising from the short time duration of the involved pulses manifests itself, however, in their broad spectral bandwidth and the resulting low spectroscopic selectivity for addressing, for example, energetically closely spaced states with the pump pulse.

4. Attosecond photoemission spectroscopy of solids

The first attosecond experiments on solids were using the attosecond streak camera and later also RABBITT to resolve the photoemission dynamics from solid surfaces [16, 17]. The first streak camera experiments measured the timing between electrons photoemitted from the conduction band of a W(110) crystal with respect to electrons from the localized tungsten 4f core states [16]. RABBITT experiments on Au(111), Ag(111) and Cu(111) added energy resolution to the timing information and provided absolute delays calibrated against photoemission from argon atoms, which can be reasonably well calculated from theory [17, 18]. While the delays observed in previous experiments were consistent with assuming that the photoemission dynamics is dominated by ballistic transport of quasi-free electrons over an inelastic mean-free path to the surface, the RABBITT experiments revealed evidence for band-structure effects in the observed energy-dependence of the delays [18].

While our understanding of photoemission dynamics from solid surfaces is improving rapidly, many important questions remain open. Presently, the dynamics is interpreted in a three-step process that consists of excitation, transport to the surface and emission into the vacuum. This three-step model of photoemission is, of course, only an approximation of a true quantum mechanical description and it is known to fail under certain circumstances. With one notable exception [19], the experiments performed so far could satisfactorily be explained considering only the transport part of the three-step model. When do the other two steps need to be included and when does this three-step picture of photoemission fail altogether to properly describe the dynamics?

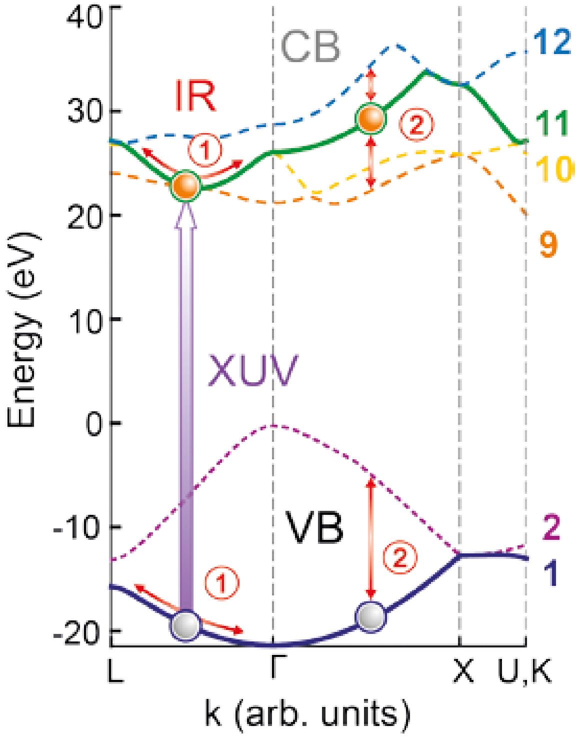


Figure 3: Intra- and inter-band dynamics. The illustration shows few selected sub-bands of the bandstructure of diamond. The horizontal red arrows represent infrared field driven intra-band electron motion (1) while the vertical arrows indicate inter-(sub-)band transitions induced by the infrared (2). The violet arrow shows the probe transition used in the ATAS experiment. The numbers on the right label individual sub-bands. The intermediate sub-bands 3-8 are not shown. (Figure reproduced from [21])

Both, attosecond streak camera as well as RABBITT, use a relatively intense infrared pulse to probe the dynamics. Past experiments show no evidence for the electron dynamics in the crystal to be modified through interaction with the infrared beam. This is not expected to hold universally. In particular for non-metallic samples, the infrared will deeply penetrate the crystal and expose the electrons to high light intensities already in the bulk. How does this infrared field interact with the crystal and its electronic structure? Can we still use the macroscopic laws of optics to describe experiments that probe dynamics on atomic spatial and temporal scales? While the Fresnel laws of optics that describe the reflection and transmission of optical waves at an interface were found to still hold on these scales for noble metals [20], it is an open question how well this finding transfers to other material classes.

5. Attosecond transient absorption spectroscopy of solids

The attosecond streak camera and RABBITT measure photoelectrons that are emitted from within few atomic layers from the solid-vacuum interface. As such, these methods are intrinsically surface sensitive. The optical absorption measured with attosecond transient absorption spectroscopy (ATAS), on the other hand, happens in the bulk of a material. ATAS therefore complements the above attosecond tool set for solid samples. While we covered the electron spectroscopy only briefly, we will give a more detailed view on ATAS and its application to different classes of solids.

As described in Section 3, in ATAS the infrared pulse assumes the role of the pump while the attosecond XUV pulse probes the induced absorption modifications. In the case of a solid, the pump serves as an external electric field that oscillates at optical frequencies and thus rapidly drives the electrons in the bulk. A question that immediately arises is whether the transient response, i.e., the direct sub-femtosecond to few-femtosecond reaction of the electronic system, is dominated by electrons being driven within their bands or by induced transitions to other bands (Fig. 3). We will address this question with experiments on two different material classes that differ strongly in their bandgap, leading to non-resonant and resonant excitation by the infrared pump, respectively.

For the large-bandgap, non-resonant case, we performed ATAS on 50-nm thick polycrystalline diamond films [21]. The thickness of the sample is dictated by the short absorption length of the attosecond XUV radiation in this material. A schematic of the used setup is shown in Figure 4a). The gas jet is used for performing a simultaneous attosecond streak camera measurement on Neon atoms. The streaking data serves as a reference to determine the exact timing

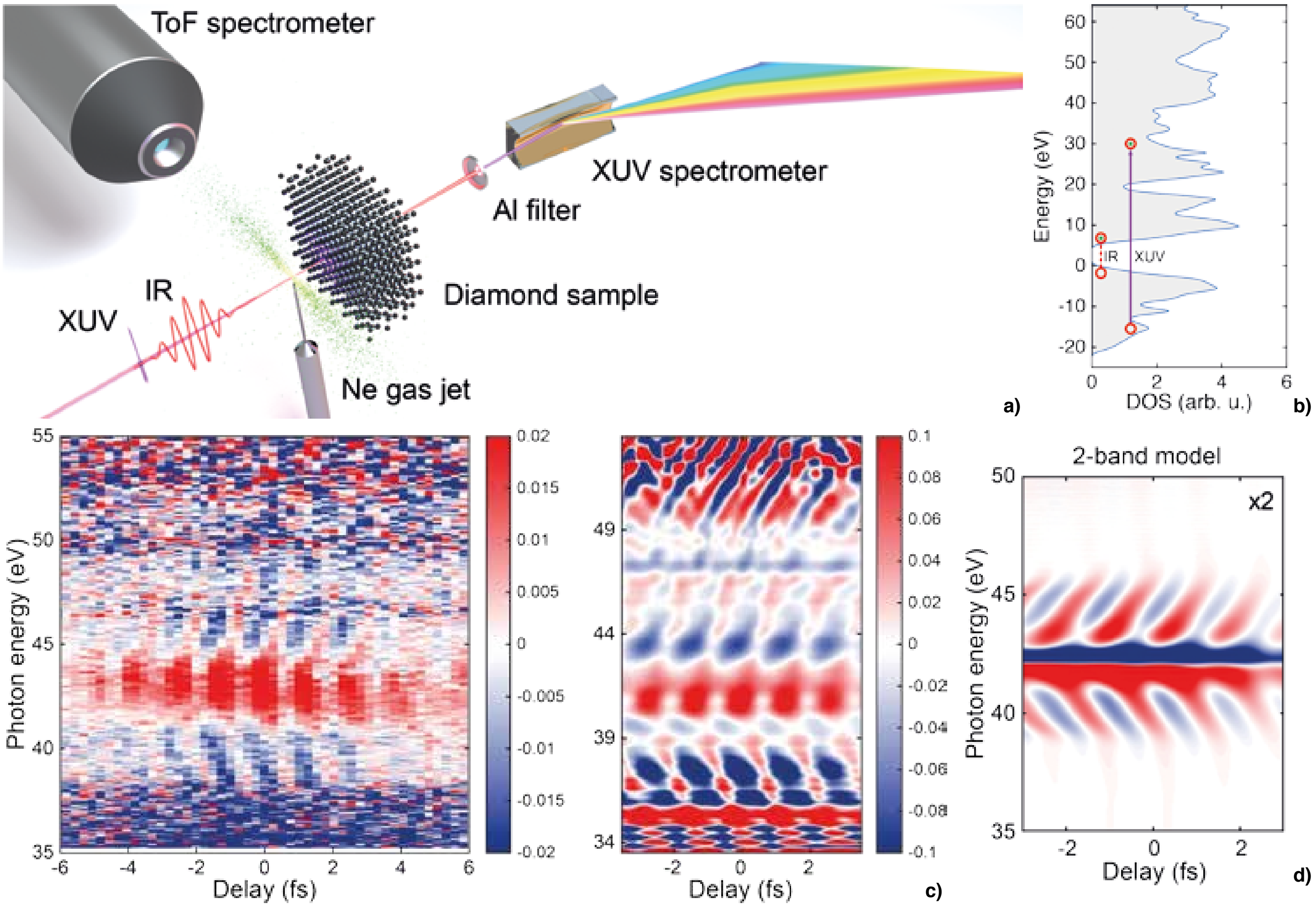


Figure 4: Attosecond transient absorption experiment in diamond. a) Experimental configuration. The Ne gas jet and the electron time-of-flight spectrometer are used to characterize the pump and probe pulses and provide the delay reference. b) While multi-photon absorption of the infrared pump can excite carriers into the conduction band, they are energetically well separated from the density-of-states probed by the attosecond XUV pulse. c) Transient absorption data (color scale indicates change in absorbance) from experiment (left) and ab initio theory (right). d) Even a very simple analytical two-band model captures the observed 'V'-shaped dispersion in the induced absorbance modulations. (Figures adapted from [21])

between the pump and the probe pulse. A simplified band diagram with the involved sub-bands is shown in Figure 3. It shows that the probe transition is from the bottom of the valence band high into the conduction band. The infrared pump photon energy is not enough to excite electrons from the valence to the conduction band. However, multi-photon transitions from the top of the valence band to the bottom of the conduction band may occur due to the relatively high infrared intensity (~10^{12} W/cm^2). Given that they are energetically well separated from the probe transition, they do not affect the measured ATAS signal (Fig. 4b).

The striking feature in the measured ATAS data are rapid oscillations of the absorption at twice the frequency of the infrared pump light. At the same time, the oscillations exhibit a 'V'-shaped dispersion with the apex of the 'V' lying at about 43 eV. To understand the observations, we performed time-dependent density functional theory. These *ab initio* calculations reproduce the qualitative signature of the measured signal well (Fig. 4c). Through an orbital decomposition and systematic elimination of unimportant sub-bands we were able to reduce the theory to only two dominating sub-bands (Fig. 4d) while maintaining the main features of the ATAS trace. Given that we only have two sub-bands left and considering the energetics, it follows that the infrared pump pulse can only drive electron motion within those bands while the attosecond pulse probes this dynamics through a transition between the two remaining bands. From this we conclude that the transient response of our diamond sample to an infrared optical field is dominated by intra-band motion rather than inter-band transitions. The observed signatures can be explained through the dynamical Franz-Keldysh effect which was previously observed with terahertz pump and optical probe pulses [21-23].

Considering the large bandgap of diamond, our findings might not be that surprising. How does the situation change if we replace the diamond sample with a 100-nm-thick crystalline GaAs membrane [24]? GaAs has a direct band gap (~1.42 eV) that is sufficiently small for a single infrared pump photon ($E_{ph} \approx 1.55$ eV) to promote electrons from the valence to the conduction band. Given that we kept the infrared intensity about the same as in the diamond experiment, one would intuitively expect that such single-photon transitions dominate the response of the material by far. In GaAs, the large bandwidth of the attosecond XUV pulse allowed probing the top of the valence band and the bottom of the conduction band simultaneously with a transition originating from the atomic As *3d* level.

The ATAS data measured in GaAs are shown in Figure 5a). The induced absorption shows again rapid modulations at twice the infrared frequency. An important difference compared to the diamond case is that the induced absorption now has a lasting tail towards positive delays. This is due to the fact that the infrared can now transfer real population in the probed energy region, which was not possible for diamond. This population thermalizes and decays again on time scales much longer than the few femtoseconds being probed here. Again we first simulate the system with time-dependent density functional theory and then try to capture the main features of the conduction band dynamics with a simplified model. In the case of GaAs, a three-band model reproduces the observed features reasonably well. In this model, the probe transition occurs from the energetically lowest band to the highest band and the pump drives transitions between the mid-energy band and the highest band. The model thus includes the As *3d* state, a valence band and a conduction band.

In this simplified model, we can selectively switch intra-band and inter-band processes on and off (Fig. 5b). By definition, only inter-band transitions can create a lasting population of real carriers in the conduction band. Rather counterintuitively, however, it is found that the transient response of the sample (i.e. the few-femtosecond overlap region of the pump and probe pulses) is still dominated by intra-band dynamics despite the infrared pump pulse now driving the valence-to-conduction-band transition resonantly. A further inspection of the model also reveals that while intra-band electron motion alone cannot inject carriers into the conduction band, the coupling of intra-band motion and inter-band transitions leads to a three-fold enhancement of the number of injected carriers compared to a situation with inter-band dynamics only (Fig. 5c) [24]. The combination of our experimental data with a comparably simple theoretical model therefore gives important insights into carrier-injection mechanisms in optically pumped semiconductors.

These examples demonstrate how attosecond science can directly reveal optical-field-driven electron dynamics in solids that were inaccessible with previous methods. Given that the optical fields oscillate at hundreds of THz, these tools yield information that is relevant for the frequency scaling of electronic and opto-electronic components and provide hints about potential fundamental speed limitations of future devices. From a fundamental physics point of view, these experiments help to refine our understanding of light-matter interaction in solids on atomic spatial and temporal scales.

6. Conclusion and outlook

The attosecond science of solids is still a rather young research field. Most studies so far have concentrated on relatively simple materials and mainly focused on general fundamental mechanisms of light-matter interaction. As the experimental and theoretical tools mature, it is expected that the field will expand towards more complex material classes. At the same time, a wide range of potentially fast electronic processes, such as charge transfer at interfaces of different materials, still awaits investigation with these new tools. Higher pulse repetition rates of attosecond sources will improve the signal-to-noise ratio [25] and will be based

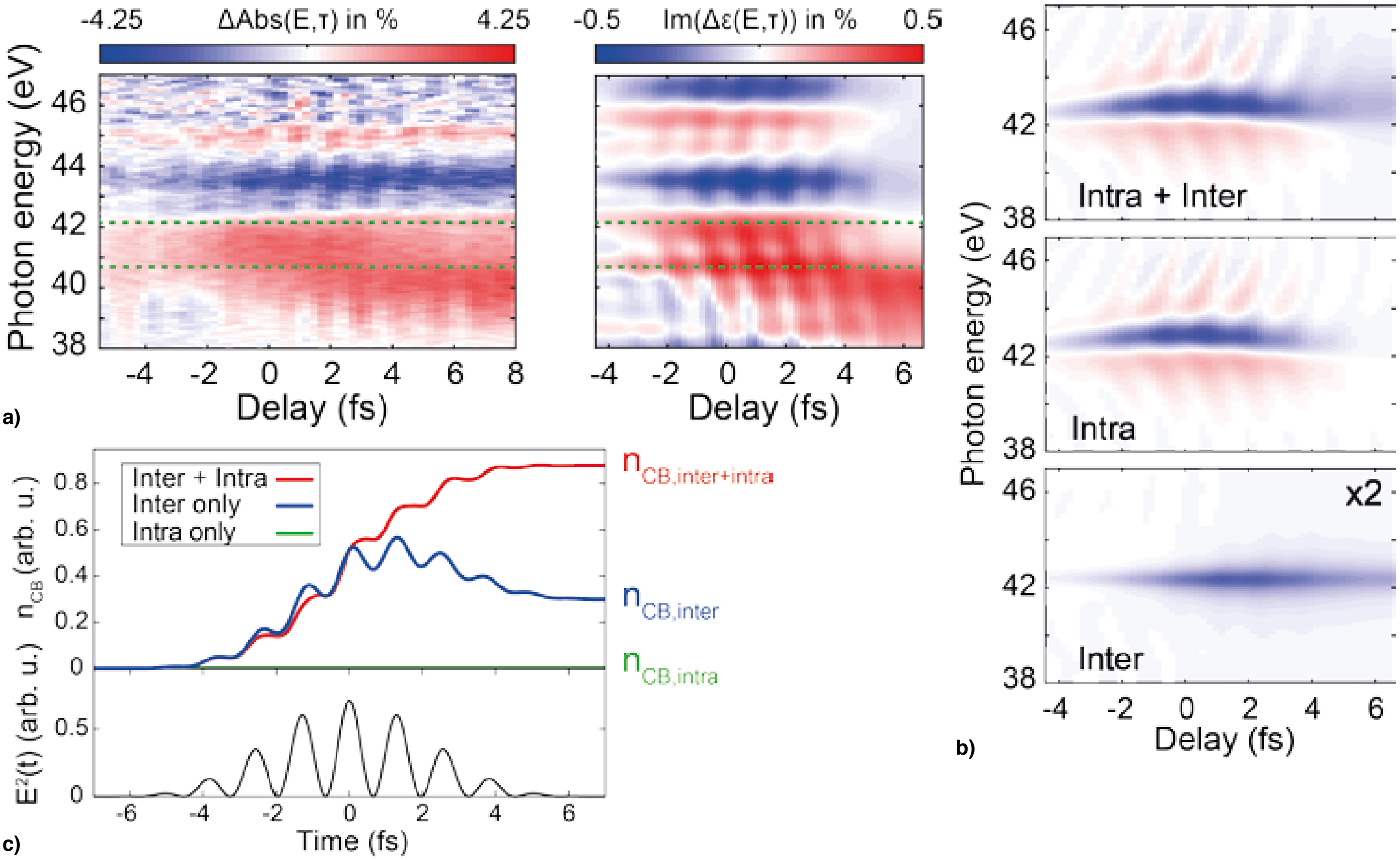


Figure 5: Attosecond transient absorption in GaAs. a) Transient absorption data (experiment, left; ab initio theory, right). The dashed green lines indicate the approximate positions of the field-free top of the valence band and bottom of the conduction band. b) Simulation of conduction band response with simple three-band model. The model indicates that the dominant features in the few-femtosecond transient response are due to intra-band electron dynamics. c) Number of carriers injected into the conduction band (top panel) and squared electric field of the infrared pump pulse (bottom panel). The coupling of intra- and inter-band dynamics results in a three-fold enhancement of the total of injected carriers. (Figures adapted from [24])

on average-power scaling of diode-pumped fiber [26], thin-disk [27] and slab [28] laser systems.

Meanwhile, with the European Extreme Light Infrastructure (ELI, [29]) becoming operational, attosecond sources will for the first time become accessible through a large user facility. Also the future ATHOS soft-X-ray beamline of SwissFEL at PSI is planned to provide an attosecond pulse mode to its users [30]. These pulses will be at photon energies that are difficult to reach with HHG and at a photon flux that is well beyond what is possible with conventional attosecond sources. Both of these developments will help to expand the community towards groups that are not specialists in the generation and handling of attosecond pulses. Through coverage of new parameter ranges, these facilities will enable entire new classes of experiments. It is expected that the few examples discussed in this article are therefore merely a beginning of the attosecond science of solids and beyond.

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Progress in Physics (67)

Philosophy of physics – what is it and why is it worthwhile to study it?

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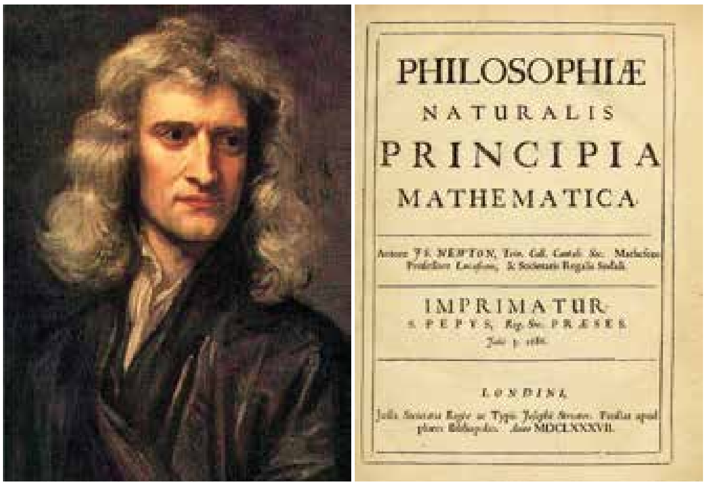
These days, philosophy seems to be ubiquitous. In bookstores, we find popular books on philosophy, business companies pretend to have their philosophy, and universities offer degrees of advanced studies in, e.g., philosophy and medicine. It should not come as a surprise then that there is also a philosophy of physics. The latter is a growing field of scholarly research, as is evident from handbooks [1, 2, 3] and textbooks [4, 5, 6] as well as from conferences and summer schools. For the next few years, it is planned that the section "History of Physics" in the SPS features more philosophy of physics. But what exactly is philosophy of physics? Is the term more than a catchword, and why should it be worthwhile to study philosophy of physics?

1. A historical route to philosophy of physics

Historically speaking, it is no accident that physics and philosophy combine within philosophy of physics. For ages, physics and philosophy have been close friends as they share a common origin. At the dawn of Western thought in Ancient Greece, physics and philosophy were indeed difficult to disentangle. For instance, when Thales of Miletus (ca. 624 – ca. 546 BC) claimed that the 'arche' (the origin, basic principle) of everything was water, or when the so-called atomists suggested that the material world consisted of little indivisible particles, they put forward what we today take to be physical hypotheses. But although the content of their views is reminiscent of physics, their method was not physical in our sense of the term; they did not run controlled experiments but instead engaged in what we may call philosophical speculation. What we can call philosophical too is their aspiration to move beyond the appearances and to understand what the world really is.

The close alliance between physics and philosophy survived until the Scientific Revolution in the 18th century. It is interesting to note in this respect that, according to its title, Isaac Newton's (1642 – 1726/27) main work on mechanics is part of natural philosophy. But further development of modern physics required increasing experimental skills and mathematical sophistication, which, in turn, effected a specialization that eventually pushed philosophers out of physics. At the same time, technological innovation and the systematic use of the method of experiment provided an increasing amount of data, which meant that less "philosophical" speculation was needed to learn about matter, its composition and the principles of its motion. But this did not mean that no task was left for more philosophically minded people. Some philosophers, notably Immanuel Kant (1724 – 1804), shifted the focus from the world to our knowledge of the world. They tried to explain how the spectacular success of modern science became possible and offered critical reflections on what they took to be the limits of science. Works such as Kant's *Critique of Pure Reason* thus paved the way to what is now called epistemology of science, which is a philosophical sub-discipline that tries to understand how science works (see, e.g., [7], pp. 1, 8). Another option for philosophers was to focus on questions that do concern the world and its structure, but to which physics does not offer conclusive answers. In this spirit, philosophers may ask, e.g., what space and time are. While, e.g., Samuel Clarke (1675 – 1729), a follower of Newton, took space to be absolute, i.e., something that exists independently of any matter, Gottfried Wilhelm Leibniz (1646 – 1716) countered that space is no more than the relationships between material beings. The discussion on this topic was constrained by the best physical knowledge of space and its structure at that time, but philosophers had to move beyond physical theories to answer the question of what space is. The challenge was to find out what the theories (at those times, Newtonian mechanics) implied for space and how this squared with our pre-theoretical understanding of space. Today, inquiries of this sort fall in the realm of what is called the *metaphysics of science*. Metaphysics is the study of the basic structure of the world. Metaphysics of science answers metaphysical questions by drawing on our best theories from the natural sciences.



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

IMPRIMATUR

Fig 1: Isaac Newton (left panel) published his theory of motion and gravitation in his „Principia" (right panel), a work that is supposed to contribute to philosophy.

Fig 2: Immanuel Kant, in his „Critique of Pure Reason", tried to explain how it was possible to obtain the physical knowledge of his time.

While, in the 19th century, to some extent, physics and philosophy parted company, and some physicists became hostile towards any metaphysics, things changed dramatically during the first half of the 20th century. According to historian and philosopher Erhard Scheibe, physicists turned philosophical (again) at that time [8]. The reason was that Albert Einstein's theories of relativity and quantum mechan-

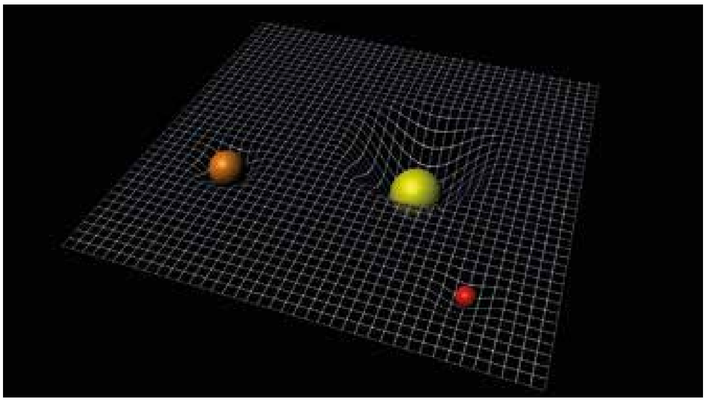


Fig 3: According to Albert Einstein's General Theory of Relativity, space-time can be curved, as illustrated in the viewgraph. This challenged Immanuel Kant's view that space can be known to be Euclidean independently of experience.

ics challenged not just popular philosophical views about science and its findings, but also shattered common sense about objects, space and time. For instance, if simultaneity is relative to observers, as famously argued by Einstein, how can we talk about the present ("the now") that is common to several people? Or how can light be a wave, while still being composed of particles (photons)? Physical theories provided "food for thought" and physicists themselves such as Werner Heisenberg (1901 – 1976), but also philosophers, e.g., Hans Reichenbach (1891 – 1953), immediately began to address such questions.

Fig 4: Hans Reichenbach was among the first philosophers who discussed Einstein's theories of relativity from a philosophical perspective.

The questions raised by the new theories proved difficult to answer, and most of them are still on the research agenda. But these days, they do not much occupy physicists anymore. Rather, the questions are addressed in a field that is now called *philosophy of physics*. The advent of philosophy of physics marks a new wave of specialization with its own division of labor. Very roughly, physicists concentrate on the application and further development of their theories, while philosophers of physics try to make sense of the puzzling features of those theories.

2. Philosophy of physics today

Philosophy of physics may be defined as a philosophical reflection about physics and its theories. It is one of the philosophies of the special sciences, and thus parallel to, e.g., philosophy of biology. The philosophies of the special sciences have partly been formed because it was increasingly realized that general philosophy of science is under threat of over-generalization.

As any philosophy of a particular science, philosophy of physics can be split in an epistemological and a metaphysical part, as indicated above. But today, philosophy of physics is mainly metaphysics of physics. The most important reason for this is the puzzling nature of many physical theories.

Methodologically, philosophy of physics (in what follows in the sense of metaphysics of physics) relies upon physics, because it draws on its theories. The focus is on well-established theories because only these theories promise insight into how our world is like deep down. But occasionally, less well-established theories, e.g., of quantum gravity are investigated to arrive at hypothetical results about how the world would look like if a certain theory was true. The challenge for philosophers is in any case to make sense of a specific theory or to show how several theories that seem incompatible fit together. To this purpose, it is essential to clarify what the basic concepts in which the theories are cast mean. But it is maybe easiest to introduce research in philosophy of physics using an example.

3. An example: the interpretation of quantum mechanics

Well-known axiomatic representations of non-relativistic quantum mechanics (QM) contain not just the Schrödinger equation for the wave function, but also a distinct postulate about measurements (which is often called collapse postulate). It is baffling that a physical theory that is supposed to be fundamental treats measurements in a separate manner. This puzzle is at the center of the so-called measurement problem. In its modern formulation [9], it arises because three well-established principles clash with each other:

a. The linear Schrödinger equation fully governs the dynamical evolution of non-relativistic quantum systems.
b. The outcomes of measurements on such quantum systems are fully determinate and unique.
c. QM is a fundamental theory in that there are no degrees of freedom not implicit in the wave function.

The principles lead to a contradiction: Since the Schrödinger equation is linear, superpositions of two solutions to it solve the equation too. For instance, the eigenstate of the spin of an electon in the z-direction is a symmetric superposition of the two eigenstates of spin in the y-direction. Each of these eigenstates would lead to a measurement outcome of spin up or down in the y-direction, respectively. Thus, if (a) is true, then, during a measurement of spin in the y-direction on the z-eigenstate, the wave function representing the electron and the measurement apparatus is in a superposition of two states that correspond to a measurement of spin up and one of spin down. But following (b), the measurement result is not a superposition of spin up and spin down; instead, the measurement yields either spin up or spin down in the y-direction. This means that, either, the Schrödinger evolution is interrupted to yield a determinate outcome or that degrees of freedom not implicit in the wave function fix the outcome. Thus, we obtain a contradiction with either (a) or (c).

To avoid the contradiction, a resolution of the problem has to deny at least one of the three principles. In the last two decades, detailed proposals have been put forward in this respect. Typically, they do not just reject one of the principles, but rather provide a more comprehensive picture of the quantum world and its ontology (e.g., the kinds of things that exist at the quantum level). The so-called Ghirardi-Rimini-Weber theory (GRW), for instance, denies (a), the idea being that the Schrödinger evolution is interrupted by so-called hittings (random events) which lead to what is considered the collapse of the wave function during measurement. The deviations from the Schrödinger evolution that ensue are so minimal that they cannot be observed with our present means, but they may become observable in the future. The many-worlds interpretation, in turn, denies that there are unique determinate outcomes of measurements. Instead, when a measurement occurs, a branching takes place, and different versions of an observer witness different outcomes depending on their branch. So what is characterized by the wave function is actually a tree of branching worlds, which each lack the puzzling features of QM. The so-called Bohmian version of quantum mechanics, in turn, denies (c) and holds that quantum mechanics is ultimately about classical particles with determinate locations and momenta, which form degrees of freedom not captured by the wave function. This function is only used to determine their dynamics by providing a guiding field for them.

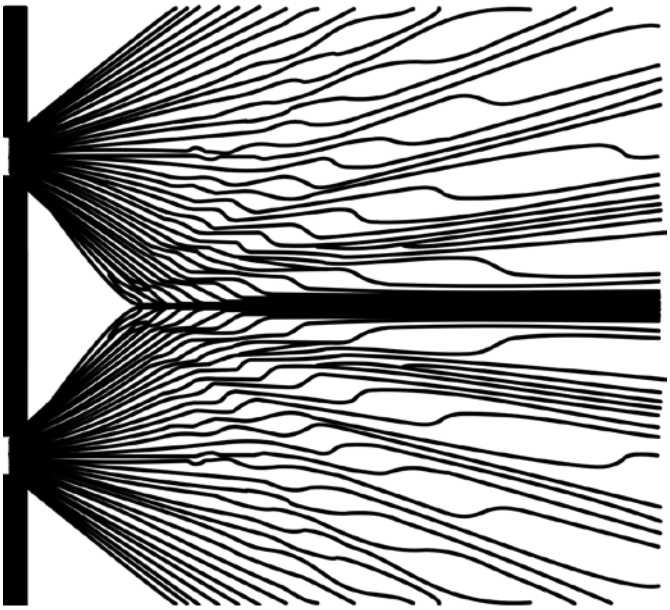
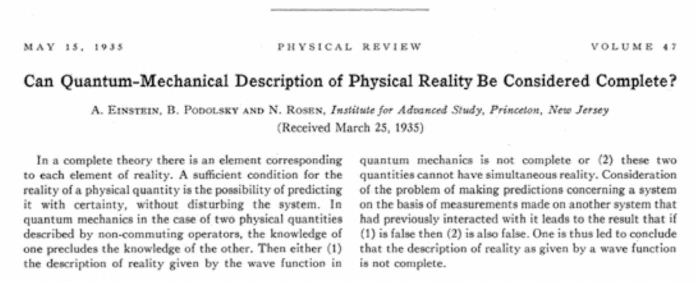


Fig 5: According to Bohmian mechanics, the wave function is used to trace the dynamcis of particles with fully determinate trajectories in space. This viewgraph shows the trajectories of electrons for the double-slit experiment.

What we obtain in this way are various interpretations of quantum mechanics: They give competing accounts of what the quantum world is like according to standard non-relativistic quantum dynamics or a slight variation of it (GRW). There is no doubt that the various views come with their problems: Bohmian mechanics, for instance, is difficult to generalize to non-relativistic QM. The many-worlds theory, in turn, seems barely intelligible. It is no surprise then that philosophers have looked for alternatives. One prominent strategy to do so is to qualify QM as less important and to claim that crucial parts of the formalism of standard QM do not specify features of the real world. Rather, e.g., the wave function is supposed to only serve as a bookkeeping device that helps physicists to forecast the outcomes of measurements. This, then, is a task for philosophers of physics too: They need to decide to what extent physical theories deserve a realist treatment, i.e., to what extent they deliver true descriptions of reality rather than being mere instruments that do not represent how the world is.

In any case, the last two decades have seen tremendous efforts to render the various accounts of QM palatable, and there are lively debates between the proponents of the various theories. Of course, the controversies cannot be decided on the basis of data alone; instead, appeal to theoretical virtues such as simplicity, parsimony or consistency with other knowledge about the world is necessary to compare the theories. This, maybe, is characteristic of philosophical theorizing, but it is arguable that the theoretical virtues appealed to by philosophers are no different from those used in physics. It is further obvious that we do not really understand what quantum mechanics tells us about the real world if we do not engage with the various interpretations.



MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

Fig 6: In a famous paper from 1935, Albert Einstein, Boris Podolsky and Nathan Rosen raised the question of whether quantum mechanics delivers a complete description of physical reality.

4. Other topics in the philosophy of physics

Of course, modern physics offers more food for thought than does quantum mechanics, and there are various other topics in the philosophy of physics. To begin, consider statistical mechanics as a prominent example. What is puzzling here is that the material macro-world features many processes that are irreversible, i.e., that only occur in one direction, although the relevant microphysics seems time-reversal invariant. Thus, coffee with milk is never observed to unmix spontaneously or to heat up at the expense of the temperature of the environment, although the fundamental laws of physics allow for this. One much-discussed answer to this puzzle holds that a special initial state of the Universe explains the existence of irreversible processes [10]. What is a matter of controversy here too (as it is in quantum mechanics) is the understanding of the probabilities used in statistical mechanics. Can we be realists about them and claim that they describe chances in the real world or are they merely devices to express our uncertainty about degrees of freedom we do not know much about?

Another focus of philosophy of physics is space and time. As indicated, the nature of space-time was already a matter of debate in the 18th century. Today, the question of whether space-time is independent of matter continues, but now under the auspices of general relativity (GR). The impact of GR on the status of space-time is mixed: On the one hand, as the name suggests, GR is a clear departure from absolutist conceptions of space, as defended by Clarke. On the other hand, according to GR, space-time is the bearer of highly non-trivial properties, e.g., curvature, and GR has non-trivial vacuum solutions, which indicate that space-time structure is independent of matter. Theories of quantum gravity, which are not yet well established though, suggest that time, and, maybe, even space emerge from more fundamental structures.

There are more physical theories, notably classical mechanics and electrodynamics, not to mention quantum field theory, that raise philosophical puzzles and that are investigated by philosophers. Physical cosmology also raises interesting issues. But we cannot further delve into them here.

5. Conclusion

Richard P. Feynman is sometimes said to have commented that philosophy of science is as useful to scientists as is ornithology to birds. There is indeed a type of philosophy of science that is not particularly useful or interesting to scientists, viz. an epistemology of science that is mainly about science and scientists. This type of philosophy is not concerned with the type of questions that scientists themselves address. Present-day philosophy of physics is different. It shares with physics a deep interest in the structure of the material world. It is based on physical theories and tries to understand what those theories imply for our understanding of the world. It uses the same sorts of concepts that are employed by physicists and can thus help physicists to better grasp and further develop them. In the 20th century, it was physics itself with its puzzling theories that has necessitated a philosophical inquiry into their meaning. We can thus hope that more philosophy of physics in the SPS will not just engage a small group of philosophers, but also physicists from various branches of the discipline.

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International Day of Light 2019

Bernhard Braunecker, SPG, Christoph Harder, Swissphotonics

It has become a fixed ritual at UNESCO to celebrate the International Day of Light every year in May. The aim is to draw global awareness to the achievements of the science of light and its numerous applications, as well as to the general significance of light for humanity. The choice of the month of May refers to May 16th, 1960, when the American physicist Theodore Maiman (1927 - 2007) succeeded for the first time in emitting *directed* light, which we nowadays call laser light. The completely new properties of laser light have influenced our world to such an extent that we are already speaking about the 21st century as the century of light.

International
Day of Light
16 May

As in previous years, the organizers of IDL2019 would like to encourage people worldwide to organize events in May 2019 that deal with the subject of light and its technical-scientific or artistic-cultural aspects in a way that everyone can understand.

Special target groups are

- Young people in education who should become acquainted with the extraordinary potential of photonics, i.e. modern light science, in order to plan their professional future with optimism,
- Artists and creators of culture, to whom completely new design possibilities open up if they also include light phenomena like projections in their works.
- Scientists who, on the one hand, are creating the basis for micro-optical components to increase data communication rate by several orders of magnitude, but also to build huge laser facilities to perform nuclear fusion processes, as they take place on the sun, which in the long term will lead to new energy sources,
- Technicians who add photonic technology to electronic devices to improve their performance significantly as mentioned in data communication or in innovative parallel computers, but also to material processing where lasers will replace mechanical drilling and milling machines. And modern 3D laser printing systems allow to generate objects from organic substances.

Therefore, if you feel addressed and if you are considering to organize actions, concerts, light shows, exhibitions, vernissages, seminars, etc. related to light in a broader sense, you may upload your event on the UNESCO website in the IDL2019 calendar, thus ensuring great national and international visibility. All you have to do is go to https://www.lightday.org/events, then click on "***Submit an Event***" and describe your event in a few words. If your request is then included in the calendar, which will usually be the case, you can also use the official IDL2019 logo to advertise your event free of charge and with no further obligations. If we can advise or assist you, please do not hesitate to contact us.

Milestones in Physics (15)

New Materials:
Symmetries, Dimensions, Structural Order and Disorder in Solids (part 1)

Hans Rudolf Ott, ETH Zürich

PRELUDE

Symmetries, dimensions, order and disorder play an essential role in the physics-based description of nature in general. In this brief overview we shall concentrate on a very limited range of such aspects in the physics of condensed matter without considering liquids and so-called liquid crystals. In this essay we also do not consider crystals based on arrangements of organic molecules and bio-relevant materials, often termed soft matter and films.

Since the early 20th century, i.e., since the pioneering experiments employing x-ray diffration, inspired and lead by Max von Laue [1], inorganic solids are considered as three-dimensional (3D) objects, built from regular, translationally periodic, long-range ordered arrangements of atoms or molecules. Formally, such *crystalline* objects in the form of single crystals and polycrystals are structurally described on the basis of space (Bravais) lattices of different symmetries, decorated with motives of atomic configurations, again exhibiting various symmetries and kept together by characteristically different bonding interactions. In three dimensions (3D), fourteen different Bravais lattices, finally resulting in 230 space groups or „structures“ are possible. Another variety of solids, termed *amorphous*, reveals atomic order on a short-range scale, of the order of interatomic distances. This includes so-called glasses which may be considered as frozen liquids.

Structurally long-range ordered materials are crystalline solids consisting of pure elements or compounds with well defined chemical compositions invoking integer numbers of atoms per formula unit. Alloys, a term usually applied for metallic materials, are considered as solids for which only the average chemical composition is defined. This automatically leads to some degree of disorder, both structurally and chemically. Nevertheless, alloys are well known to play a major role as materials employed in technical applications. After World War II, experimental investigations of physical properties of solids first concentrated on materials in single- and/or polycrystalline form. Only after 1960, solids in other forms, to be discussed below, received growing attention.

A. QUASI-CRYSTALS

I. Long-range orientational order without translational symmetry

In November 1984, Dan Shechtman and collaborators reported the growth of metallic solids based on alloying Aluminium (Al) with, of the order of 10 to 14%, Manganese (Mn) [2]. Selected-area electron diffraction on individual grains resulted in spots claimed to be as sharp as those usually obtained from crystals but their indexing to any Bravais lattice failed. The recorded spot patterns revealed long-range orientational order and an icosahedral point group symmetry, inconsistent with translational symmetry or periodicity, the basic symmetry of then known crystalline solids. In retrospect, this discovery, which was later honoured with a Nobel Prize, can safely be considered as a milestone in the physics of solids.

Unknown to most and almost coinciding with the submission date of the paper cited above, Tsutomo Ishimasa and Hans Ude Nissen of the Laboratorium für Festkörperphysik at ETH presented an unpublished report on the discovery of a new ordered state in small Nickel-Chromium (Ni-Cr) particles at a local meeting in Switzerland [3]. Diffraction patterns of these particles revealed a twelvefold symmetry axis which, again, according to conventional wisdom, is not allowed in translationally periodic crystal structures. Not surprisingly they immediately submitted an article which eventually got published in a journal with higher visibility [4] by claiming to have found a new state of structural order in solids, intermediate between crystalline and amorphous, a crystalloid as defined earlier by A. L. Mackay [5]. Within a short period of time, similar observations were reported in the literature. Probably the first structure model for describing quasicrystals suggested to apply a three dimensional Penrose tiling model [6, 7]; a number of others followed soon thereafter.

Since for many years, students in courses on solid state physics were instructed that, on simple terms, fivefold and twelvefold symmetry axes were not allowed in crystals based on periodic lattices, the cited observations clearly came as a surprise, although quasiperiodic lattices and quasiperiodic functions had been a topic in mathematics for some time. The mathematical definition of quasiperiodicity is due to Harald Bohr [8] who also authored a book entitled „Almost Periodic Functions“, which first appeared in 1932. As usual in such cases, the interpretation of the data in [2] was immediately questioned and for some time it was not entirely clear whether *Quasicrystals (QC)*, the new term introduced in [6], adopted a really alternative structural form with respect to crystals. In an early review on the structural specifics and related theoretical model descriptions which appeared in 1989 [9], this issue is discussed and it was admitted that most of the respective fundamental questions were still open. Nevertheless, the physical existence of stable quasicrystals of high quality, even allowing for the observation of defects in the quasiperiodicity, was accepted as a fact.

My interest for quasicrystals was first driven by educational motives. I thought that in my course on solid state physics, also the students should learn about the crystallography of this new form of solids right away. Related to research, a particular sentence in a critical article in which the two-time Nobel laureate Linus Pauling [10] made it clear that he didn't believe in quasicrystals, caught my eye. It stated: „*I point out that there is no reason to expect these alloys to have* *unusual physical properties.*" That was an open call for „let's find out" by experiment!

II. Crystalline, amorphous, quasicrystalline

Naturally, it has to be agreed on when physical properties may be considered as unusual! One possibility is to use this notion if physical properties are observed that do not agree with conventional wisdom or are not yet well established, both experimentally and theoretically. At the time, quasicrystals were considered by many as structurally intermediate between regular crystals and amorphous materials. It was well established that, e.g., the magnitude and temperature dependences of the thermal conductivity and the specific heat of the lattice of non-crystalline (amorphous and glassy) materials, obtained by rapid quenching from the melt, were different from those of crystalline constitution. The main experimental observations were an excess specific heat $C_p(T)$ of the lattice at very low temperatures varying linearly with T instead of the usual T^3 dependence due to phonon excitations. Likewise, the thermal conductivity $\lambda(T)$ was found to vary proportional to T^2 below a distinct shoulder or even plateau in $\lambda(T)$. It also turned out that $C_p(T)$ and $\lambda(T)$, respectively, each adopted values of almost equal magnitude, regardless of the choice of the material and the qualitative features were observed to be almost the same in very different amorphous and glassy metals and insulators [11-13]. In theoretical work it was argued that these observations could possibly be traced back to the existence of so-called tunneling states, i.e., local excitations due to motions of atoms between quasi-equilibrium positions in an almost flat energy landscape [14, 15].

In collaboration with B. S. Chandrasekhar, an ETH-guest professor from Case Western University in Cleveland, USA, we followed this up with the conjecture that also common alloys prepared using standard metallurgical techniques should exhibit a similar „glassy" behaviour because the non-periodicity is not only due to chemical disorder but also influenced by positional disorder. The latter can be identified by defining a particular atomic site by $R_i + \epsilon_i$, where R_i is the regular lattice site of the i-th atom and $\epsilon_i \neq 0$ defines the positional disorder and varies from site to site in direction and in magnitude, the latter being much smaller than the interatomic distance. The result is a high degeneracy of energetically similar atomic configurations of the positional disorder. Our experimental results of $\lambda(T)$ of a conventional Ti-V alloy supported the initial conjecture [16]. With this background we set out to test quasicrystals with respect to their physical properties at low temperatures.

It was a lucky coincidence that Hans Ude Nissen, active and highly competent in crystallography employing various techniques of electron microscopy, joined my group around 1990. Among his collaborators was Conradin Beeli, a PhD student devoting his thesis work to investigations concerning the growth of quasicrystals, their structures and models thereof. In his thesis he covered several of these aspects including a confrontation of real quasicrystalline structures, identified by using methods based on electron microscopy, with then available models [17]. This meant that we could profit from direct scientific and technical support in regard with materials' synthesis and characterization using techniques employing electron microscopy.

In our effort to investigate physical properties of quasicrystals experimentally, we were, of course, not alone. In accordance with the intention of this series I shall, however, concentrate on our contributions and refer to important work of other groups where it seems appropriate.

III. Selected physical properties of quasicrystals

III.1. Electrical Conductivity

The first attempt, together with Michael Chernikov, a postdoc at the time, consisted in measurements of the electrical conductivity and magnetoconductivity of icosahedral $Al_{70}Mn_9Pd_{21}$ with thermodynamically stable single-phase samples that we synthesized in a tri-arc furnace, followed by suitable annealing procedures [18]. Figure 1 gives an impression of the morphology of icosahedral microcrystals at the surface of as-cast material. In zero magnetic field, our data in some points confirmed the finding of earlier work on other stable quasicrystals based on alloys containing Al and d-transition metal elements [19, 20], in particular the surprisingly low electrical conductivity $\sigma(T)$ of these materials if compared with the corresponding σ-values of the constituent metallic elements. Our data could consistently be interpreted as revealing weak localization including spin-orbit scattering of the itinerant charge carriers, a topic related to disordered metallic systems [21], and Coulomb interaction effects. In our case, however, the value of the product $k_F \cdot l \approx 0.2$, where k_F is the Fermi momentum in k-space and l the electron mean free path, as deduced from parameters that entered the fits to the $\sigma(T)$ data, was found to be much below the metallicity threshold and the mentioned concepts for describing features of disordered metals [21] were therefore not expected to be valid. Indeed, our data capturing the magnetoconductivity at very low temperatures turned out to be inconsistent with the relevant predicitions of these theories, seemingly successful in periodic-lattice compounds. At the time we were unable to identify the reasons for these obvious inconsistencies.

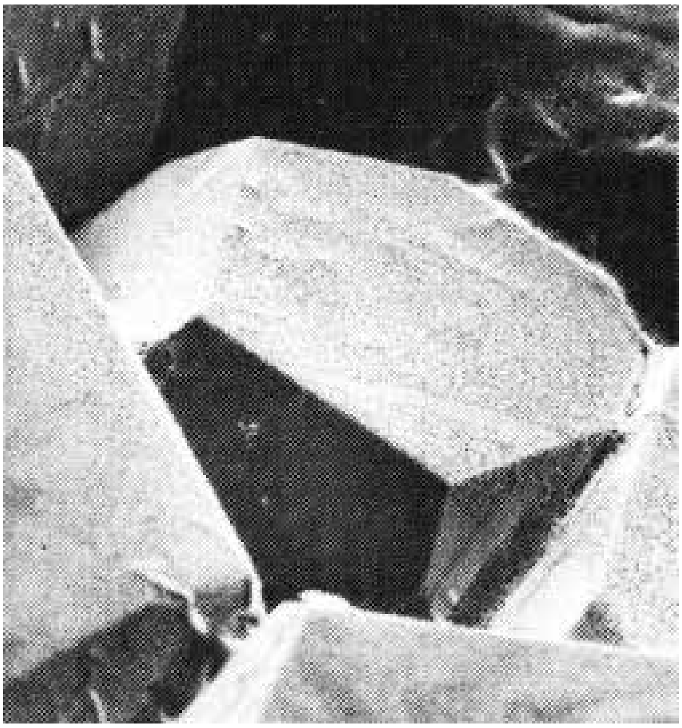

Fig. 1: Pentagonal dodecahedra with edge length of 100 µm on the surface of as-cast $Al_{70}Mn_9Pd_{21}$ (from [17]).

In order to complement the information on the electrical transport properties of $Al_{70}Mn_9Pd_{21}$ we investigated its optical properties in a broad frequency range, profiting from the relevant expertise of Leo Degiorgi, also at ETH [22]. In agreement with earlier work on other icosahedral QC with different chemical compositions [23], the electrodynamic response of the material also revealed a very low optical conductivity in the infrared regime and a substantial absorption in the visible range of the spectrum. In the cited reference [23] it was argued that the high number of reciprocal lattice vectors allows for a tight match between the Fermi surface and the respective Bragg planes, thereby creating pseudogaps in the electronic excitation spectrum and an enhancement of the effective optical mass, resulting in a corresponding reduction of the dc conductivity.

III.2. Critical electronic states

Understanding the electronic transport in quasicrystals requires a proper idea of the behaviour of noninteracting electrons in quasicrystals. The electronic energy spectrum can be calculated exactly for 1-dimensional quasicrystals but cannot be generalized to two or three dimensions [24]. It turns out that in contrast to periodic crystals, true Bloch states are not allowed in quasicrystals or, in other words, the electronic eigenstates states are not localized in k-space and therefore suffer from an intrinsic decay rate implying a non-zero electrical resistance, even in a perfect quasicrystal. Since the dynamics of itinerant electrons are essential in the relaxation mechanism related to nuclear magnetic resonance (NMR), we expected that measurements of the NMR line shift and, in particular, the spin-lattice relaxation time T_1 of quasicrystals would provide an experimental access to relevant information in this respect. For these experiments we chose another icosahedral species of quasicrystals with the chemical composition $Al_{70}Re_{8.6}Pd_{21.4}$, a rather poor metal [25]. As shown in Figure 2, its electrical conductivity $\sigma(T)$ varies approximately linearly with T below room temperature, decreasing from 35 $\Omega^{-1}cm^{-1}$ at 300 K to 5 $\Omega^{-1}cm^{-1}$ at 4 K. Below 1 K, σ saturates at 1.7 $\Omega^{-1}cm^{-1}$, corresponding to a resistivity of about 0.6 Ωcm. For comparison, the resistivity of Al at room temperature is $2.8 \cdot 10^{-6}$ Ωcm. Specific-heat data obtained for the same material confirm a very low electronic specific-heat parameter γ, of the order of only 1/10 of that of elemental Al [26].

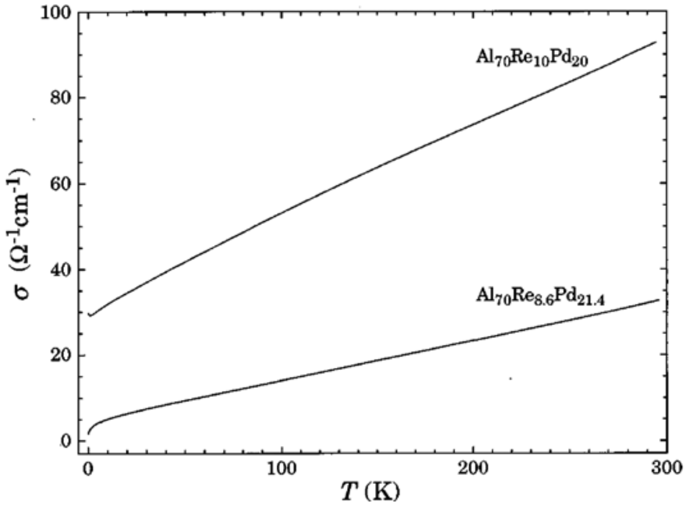

Fig. 2: Electrical conductivity σ(T) of two Al-Re-Pd quasicrystals with slightly different chemical compositions between 0.04 and 295 K.

Early results of NMR studies on quasicrystals were interpreted as confirming the very low density of electronic states at the Fermi energy $D(E_F)$, mainly indicated again by specific heat data at low temperatures [27]. With our NMR experiments, involving Jorge Gavilano, Benno Ambrosini, Patrik Vonlanthen and later Dominic Rau, we covered the temperature range between 0.04 and 300 K [28]. Below 100 K, the relaxation rate $T_1^{-1}(T)$ is dominated by the Korringa relaxation due to itinerant electrons, indicated by $(T_1T)^{-1}$ = constant. It turns out to be very weak, two orders of magnitude smaller than for Al metal. The important result of our study is the observation of a significant increase of $(T_1T)^{-1} \sim \alpha\ T^{-0.69}$ with decreasing temperature below 20 K, reflecting an increase of the efficiency of the relaxation mechanism. As may be seen in Figure 3, the enhancement of $(T_1T)^{-1}$ exhibits no trend to saturation down to 0.04 K. Ruling out a slowing down of magnetic or electronic fluctuations we argued that the most likely reason for this feature is the onset of a metal-insulator transition from the metallic side. Hence the $T_1(T)$ data are thought to reflect a gradual real-space localization which is related to critical electronic states in quasiperiodic solids. Such states are neither extended nor fully localized. With increasing localization the frequencies of the electronic fluctuations gradually shift to lower values, hence enhancing $(T_1T)^{-1}$. Assuming this interpretation to be correct, these data provide evidence for the existence of the theoretically claimed critical electronic states in non-periodic lattices [29].

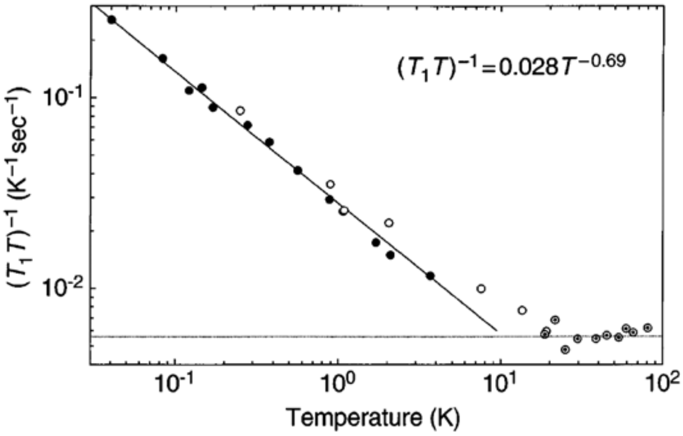

Fig. 3: $(T_1T)^{-1}(T)$ for $Al_{70}Re_{8.6}Pd_{21.4}$ below 80 K. Above 20 K, the measurements were done at 5.7 T. Data below 20 K were obtained at 1.5 T (empty circles) and 6.19 T (filled circles). The horizontal dotted line reflects the simple Korringa behaviour above 20 K and the solid line represents the indicated power-law fit.

III.3. Thermal Conductivity

Considering the seemingly universal fact of a very low concentration of itinerant electrons in stable quasicrystals, it seemed natural to assume that the thermal conductivity of these materials would be dominated by itinerant lattice excitations, i.e., phonons. Therefore we expected that measurements of this type of transport property would certainly reflect any anomalous features of the quasiperiodic lattice of these materials.

Since no experiments of this type on quasicrystals had been made at the time we, including Michael and Andrea Bianchi, a then new PhD student, set out to measure the temperature dependence of the thermal conductivity $\lambda(T)$ of, again, icosa-

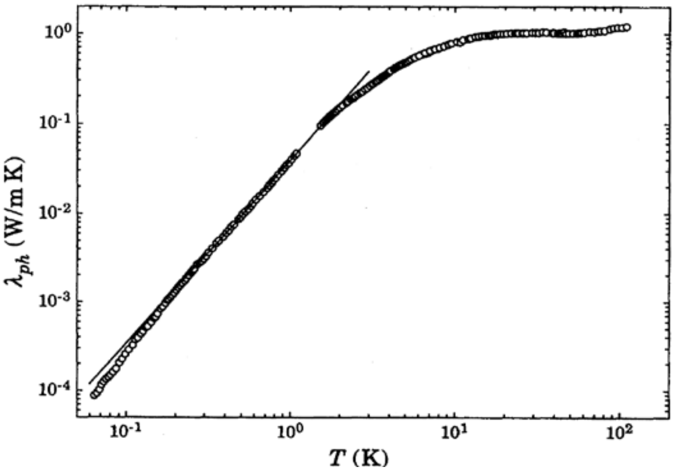

Fig. 4: Quasilattice thermal conductivity $\lambda_{ph}(T)$ of $Al_{70}Mn_9Pd_{21}$. The solid line indicates the power-law fit to the data between 0.35 and 1.6 K. The value of the resulting exponent is 2.06±0.01.

hedral $Al_{70}Mn_9Pd_{21}$. The covered temperature range extended from 0.06 to 110 K and the data revealed both common features but also distinct differences to results of disordered and/or amorphous materials cited above [30]. It turned out that the total thermal conductivity λ_{tot} is, across almost the entire covered temperature regime, an order of magnitude larger than the expected electronic contribution λ_{el}, estimated by application of the Wiedemann-Franz law. Only at $T < 0.1$ K, λ_{el} reaches 20% of λ_{tot} at most. This allowed for a fairly reliable evaluation of the phonon-based component $\lambda_{ph}(T)$ shown in figure 4. Towards the lower end of the temperature range, i.e., between 0.35 and 1.6 K, $\lambda_{ph}(T) \sim T^{2.06}$, consistent with the prediction of the tunneling-state model and assuming a continuous density of tunneling states. The presence of tunneling states in quasicrystals was also claimed from an analysis of ultrasound data [31] collected on another sample of quasicrystalline Al-Mn-Pd. It seemed conceivable that tunneling states in quasicrystals have the same origin as those observed in crystalline alloys, as mentioned above. Below 0.35 K, λ_{ph} decreases with increasing slope, obviously due to an unidentified scattering process involving phonons with a temperature independent mean free path. Above 1.6 K the most obvious feature in $\lambda_{ph}(T)$ is a well developed plateau between 25 and 55 K where $\lambda_{ph} \sim$ constant, reminiscent of the feature claimed to be typical for non-crystalline solids. This behaviour is, however, adopted at distinctly higher temperatures and the absolute value of λ_{ph} in the plateau region is distinctly higher than usually observed in insulating and metallic glassy materials.

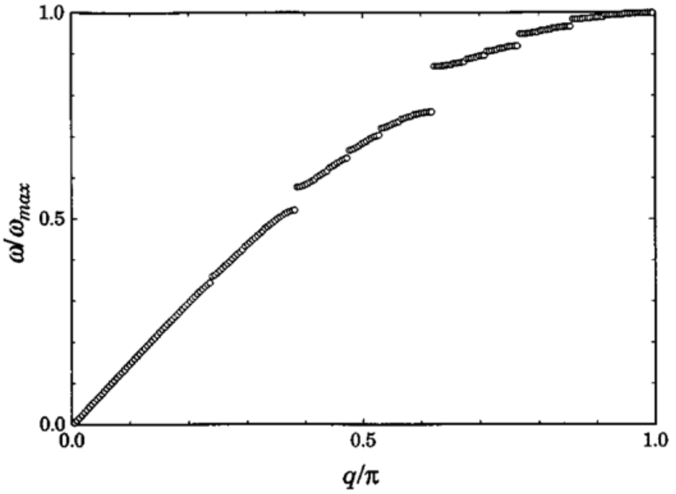

Fig. 5: Phonon-mode frequencies of a Fibonacci chain of 233 atoms with two different masses and a mass ratio of 1.5.

Meanwhile we also made attempts to dig into some theoretical aspects of the dynamics of quasiperiodic lattices. This was possible because we got help from P. A. Kalugin of the Landau Institute in Moscow, a specialist with some expertise in theories of transport properties of quasiperiodic solids and a visitor of our group for a few months. First, however, we recall that for the description of a finite thermal conductivity in periodic crystals, Peierls introduced the "Umklapp" process, reflecting the so-called structural scattering of phonons [32]. As is described in ref. [33], this type of scattering may be generalized for the case of quasicrystals where the spectrum of quasilattice modes $\omega(q)$ is distinctly different from that of periodic solids. The difference is elucidated in figure 5 where the calculated acoustic phonon modes of a Fibonacci chain of atoms with two different masses linked by identical couplings is displayed. Note the appearance of a multitude of gaps, typical for this type of quasiperiodic atomic arrangement. Following the generalization of the structural-scattering concept to three-dimensional quasicrystals we attempted to establish the consequences of this scattering invoking the example of phonon-phonon scattering and its role in the interpretation of corresponding experimental data. In the ideal case of close to perfect quasicrystals, structural scattering is expected to be reflected in $\lambda_{ph} \propto T^{-3}$ instead of the exponential temperature dependence if Umklapp processes are the main actor in perfect periodic crystals in the appropriate temperature regime. The corresponding scattering cross section, proportional to $\omega^2 T^4$, is responsible for the power-law behaviour in $\lambda_{ph}(T)$. In real quasicrystals, the expected negative slope $\partial \lambda_{ph} / \partial T$ in the Umklapp regime may be weakend, especially if the corresponding experiments are done on poly-quasicrystals where a plateau-type feature in $\lambda(T)$ may eventually result [30]. As mentioned above a regime of $\lambda(T) \sim$ constant is reminiscent of the universal feature in amorphous materials. For single-grain material, the predicted decrease of λ_{ph} with increasing temperature was found to be more distinct, however [34, 35] and consistent with the concept of gener-

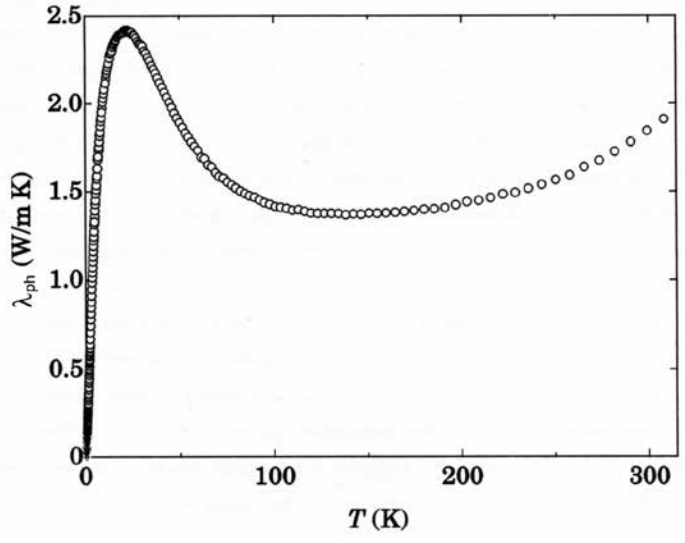

Fig. 6: The phonon contribution to the thermal conductivity of icosahedral $Y_{8.6}Mg_{34.6}Zn_{56.8}$ between 0.1 and 300 K. Its decrease with increasing temperature between 23 and 100 K is ascribed to general Umklapp scattering as explained in the text.

alized Umklapp scattering. Additional $\lambda_{ph}(T)$ data probing an icosahedral single-grain quasicrystal $Y_{8.6}Mg_{34.6}Z_{56.8}$ between 0.1 and 300 K by Alex Sologubenko and Konrad Gianno, clearly confirmed the contribution due to generalized Umklapp scattering. As shown in figure 6, it dominates in the temperature range between 25 and 140 K. Indeed, no clear evidence for the presence of tunneling states was obtained and therefore, these states are not necessarily a universal ingredient of quasicrystals, especially if these are of exceptionally high structural quality [36]. This result may be interpreted as evidence that possible tunneling states are essentially based on imperfections in the atomic arrangements of the lattice.

Due to the availability of Al-Cu-Co single-grain decagonal quasicrystals which share structural properties of solid matter with both periodic and quasiperiodic lattices we, together with another temporary guest of our group, Keiichi Edagawa from the ISSP in Tokyo, were able to investigate the thermal conductivity $\lambda(T)$ of periodic and quasiperiodic features of the lattice on a single sample along different directions of $Al_{65}Cu_{20}Co_{15}$ [37]. The direction of lattice periodicity is along the decagonal axis and the quasiperiodic arrangement is in the plane perpendicular to it. With regard to dimensions it may be noted that in five dimensions the relevant space group is $P10_5/mmc$ [38]. The results for $\lambda_{ph}(T)$ are shown in figures 7a and 7b and the direct comparison demonstrates the difference quite clearly. Along the quasiperiodic direction (fig. 7a), the features are again the same as exemplified above for the overall quasiperiodic lattices. The influence of the generalized Umklapp scattering is emphasized in the inset by choosing an expanded vertical scale. Along the periodic direction, however, $\lambda_{ph}(T)$ exhibits features that are well known from periodic-lattice materials with a maximum around 20 K, marking the transition to Peierls' Umklapp scattering with increasing temperature (fig. 7b). The power-law type of variations below 1 K are most likely due to electron-phonon scattering (fig. 7a, b).

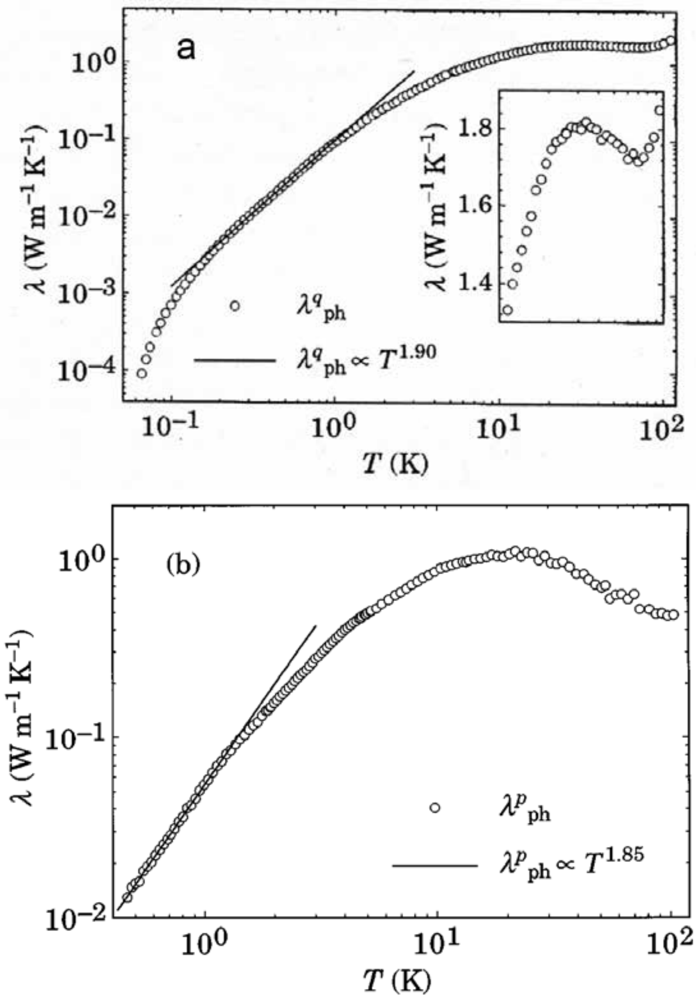

Fig. 7: Quasilattice thermal conductivity $\lambda_{ph}(T)$ of $Al_{65}Cu_{20}Co_{15}$ along (a) the quasiperiodic and (b) the periodic direction, respectively. The solid lines indicate the power-law features in limited temperature ranges.

III.4. Compressibility

Another physical quantity which is strongly influenced by the symmetry of the crystal lattice is the compressibility. Early work [39] using resonant ultrasound spectroscopy (RUS) [40] had verified the expected [41] overall elastic isotropy of an icosahedral single-quasicrystalline Al-Cu-Li alloy with a high level of confidence.

Our effort involved the determination of the complete set of elastic constants $c_{ij}(T)$ between 5 and 290 K, also employing the RUS technique on a decagonal single quasicrystal with composition $Al_{71}Ni_{16}Co_{13}$ [42]. The number of independent elastic moduli c_{ij} is five. The experiment was done during one of my then annual visits to Los Alamos National Laboratory (LANL) and profited very much from the expertise and help of Albert Migliori and T. W. Darling in employing the RUS method, not only with respect to the sample holder and the ultrasound equipment but, in particular, also in applying the special codes for the rather involved data analysis. Decagonal quasicrystals are expected to exhibit transverse elastic isotropy, i.e., in the plane with the non-periodic pattern of the atomic configuration. For periodic crystals, intrinsic transverse isotropy is only expected for hexagonal lattices. It can be identified by calculating two quantities, A_s and A_c, both combinations of the individual elastic constants c_{11}, c_{12} and c_{66}. In case of transverse elastic isotropy, $A_s = A_c = 1$. In figure 8 it may be seen that for our Al-Ni-Co QC this condition is fullfilled within very narrow margins. The comparison with reanalyzed RUS data of a hexagonal $NbSi_2$ single crystal [43] not only emphasizes the quality of the experiment and its analysis but also the high structural quality of the probed quasicrystalline sample. By using the advantage of the availability of the complete set of elastic constants we also calculated the polar anisotropy param-

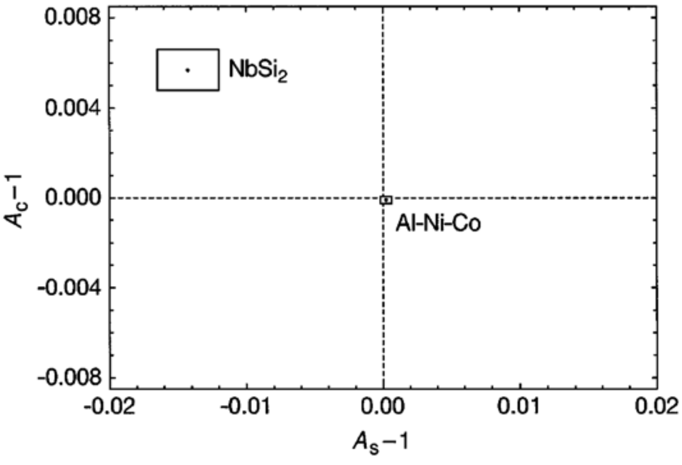

Fig. 8: $A_c - 1$ vs $A_s - 1$ for decagonal single-quasicrystalline $Al_{71}Ni_{16}Co_{13}$ and hexagonal $NbSi_2$, respectively. The experimental uncertainties are indicated by boxes.

eter $P_c = c_{33}/c_{11} = 0.991$. This rather unexpected result indicates almost equally strong bonds between atoms in the quasiperiodic plane and along the periodic direction, hence resulting in a close to overall elastic isotropy of this decagonal quasicrystal. This type of information is important for theoretical calculations regarding the stability of quasicrystalline matter.

III.5. Lattice Dynamics

Theoretically, icosahedral quasicrystalline lattices may be viewed as periodic crystals in six dimensions (6D). They allow for two types of excitations, phonons and phasons in three branches each [41, 44]. Phonons are the usual collectively propagating lattice waves. Phasons, however, are local atomic motions or rearrangements which occur in discontinuous jumps and, in comparison with crystalline periodic solids, are a specific feature of quasicrystals. The consequences of this atomic motion are expected to influence the physics of quasicrystals in many respects, such as phase transitions, lattice stability and internal diffusion. In common crystals, bulk self-diffusion relies on the existence of vacancies in the atomic arrangement forming the lattice and it can be measured with various techniques. However, for quasicrystals, considering the phason modes, Kalugin and Katz [45] claimed that bulk diffusion in this case is easier achieved by phason flips rather than moving vacancies. The resulting anomalous motion may be described by a diffusion coefficient of the form $D(T) \sim D_0 \cdot \exp(-\epsilon/k_B T)$ with ϵ as a usually temperature-dependent activation energy [46, 47]. It is resonable to assume that the activation energy of the atomic motion due to phason slips is very low and therefore, this type of motion is expected to dominate the self diffusion in quasicrystals at very low temperatures. The conventional diffusion due to vacancy motion, however, is expected to be of significance only above room temperature. Employing the usual radiotracer techniques it was shown that at temperatures exceeding 700 K, the diffusion in quasicrystals was not significantly different from that of crystalline material and by extension of the covered temperature range to 520 K, diffusion constants of the order of 10^{-22} cm²/s were deduced [48].

In order to gain experimental evidence for the quoted anomalous atomic motion we employed the experimental approach of two-dimensional Exchange NMR (2D NMR), probing the ^{27}Al nuclei in $Al_{70}Re_{8.6}Pd_{21.4}$, the same sample that was previously investigated in the 1D NMR study of line shapes and spin-lattice relaxation reported in [28]. Of great help in performing the new experiment and the data analysis was Jani Dolinšek from the Josef Stefan Institute at Ljublijana, visiting our group for a few weeks.

Relevant technical aspects of 2D exchange NMR measurements are described in [49] and more specific details, relevant for our case, may be found in [50]. The essential quantitiy to explore with this technique is the average time constant τ_{exch} for atomic jumps. Its inverse, $1/\tau_{exch}$, may be interpreted as an average jump rate. The related diffusion constant is then defined by $D = l^2/\tau_{exch}$ with l as the elementary jump length of the order of 0.1 nm, i.e., shorter than the nearest-neighbour distance in the QC structure. The measurements were done in the temperature range between 0.16 and 130 K where the dominance of the phason-slip induced motion is expected to show up. The experiments turned out to be very time consuming; establishing a single useful data point took between 1and 3 days and therefore, the density of data is rather low.

Our data in the form of 2D NMR spectra and the corresponding temperature dependence of $1/\tau_{exch}$, the latter being plotted in figure 9, provided the first clear evidence of the phason-type dynamics in quasicrystals in the low-temperature regime extending significantly to below 1 K [51]. The motion, which occurs on a much faster time scale than expected from an extrapolation of the data obtained for bulk diffusion above 520 K, persists to the lowest temperatures and is, contrary to normal diffusion, spatially confined. The latter is evident from the shape of the 2D NMR spectra and this observation provides evidence that this motion is indeed a phase-slip induced diffusion via quantum tunneling below 1 K and thermally activated above (see inset of fig. 9). Details concerning the experiment, the data and their interpretation, are offered in [51].

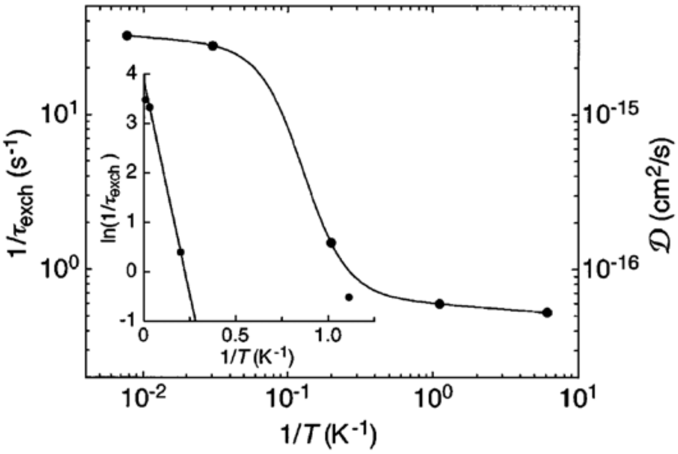

Fig. 9: $1/\tau_{exch}$ vs T^{-1} on logarithmic scales; the solid line is to guide the eye. The inset captures $\ln(1/\tau_{exch})$ vs T^{-1} and allows to estimate the activation energy ϵ that is related to phason motion. The scale of D(T) assumes an average jump length of 0.1 nm.

III.6. Magnetic properties, specific heat and the stability of magnetic moments in QC

An early study of magnetic properties of quasicrystals was based on measurements of the magnetic susceptibility and nuclear magnetic resonance and aimed at comparing the magnetic behaviour of crystalline and quasicrystalline phases of Al-Mn-Si-Ru alloys. The authors conjectured that the differences did not so much depend on the symmetry of the atomic lattices (periodic vs nonperiodic) but rather on the details of their atomic configuration [52]. In both types of the lattice, the formation of spin-glass phases were observed whereby the respective freezing temperatures of the order of 10 – 20 K of the two lattice species were not distinctly different.

In our first attempt in this respect and with most valuable support from our technician Erich Felder, we investigated the specific heat $C_p(T)$, the magnetic susceptibility $\chi(T)$ and the magnetization $M(H)$ at constant temperature of icosahedral $Al_{70}Mn_9Pd_{21}$ [53]. In order to avoid complications in data interpretations, all experiments were done using the same sample as in [18]. From $C_p(T)$ measured between

0.06 and 18 K we confirmed a very low value of the density of electronic states at the Fermi energy $D(E_F)$, in turn consistent with a very low density of itinerant charge carriers as expected when considering the above-mentioned pseudo-gap formation in the electronic excitation spectrum (see III.1). This evaluation was somewhat hampered by the presence of a substantial excess specific heat below 8 K, essentially due to magnetic degrees of freedom related to the Mn atoms. From plots of the inverse dc susceptibility we derived a mean effective moment of 1.7 μ_B/Mn and a Curie-Weiss temperature θ_{CW} = -108 K above 50 K, indicating an antiferromagnetic interaction between the Mn moments. At lower temperatures, below 4 K, these values are reduced to 0.47 μ_B/Mn and -0.54 K. The result of measurements of the low-field ac magnetic susceptibility revealed a frequency dependent spin-glass transition in the range of 0.5 to 0.55 K which, in comparison with the θ_{CW} value valid at $T > 50$ K, indicates a high degree of magnetic frustration, in spite of the structural perfectness of the sample. The degree of frustration is much larger than usually observed in canonical spin glasses established in crystalline alloys. From a detailed discussion of the thermodynamic data we argued that the transition was entropy driven rather than due to simple energy considerations.

The stability of magnetic ions in a metallic environment has been a topic of high interest during a long period of time [54]. Therefore it seemed appropriate that also quasicrystals, although rather bad metals, ought to be investigated in this respect. Obvious candidates for this type of studies are alloys with Mn as one of the chemical components, such as Al-Mn-Pd and Al-Mn-Ge QC. The results of a number of different studies indicated that, depending on the chemical composition and the adopted quasicrystalline structure, paramagnetic-, ferromagnetic-, diamagnetic and spin-glass type features had been observed. In view of the non-periodicity of the lattice, claims of ferromagnetic order [55] that extends across the entire QC sample should, as discussed in [56], be viewed with caution because there were some experimental indications that not all the Mn ions carry a magnetic moment.

As described above, our initial experiments in this respect [53] revealed that in icosahedral $Al_{70}Mn_9Pd_{21}$ effective magnetic moments, of the order of 0.5 μ_B/Mn survive at very low temperatures, weakly interacting antiferromagnetically and adopting a spin-glass ground state. Based on a closer examination of the data in this work and the conclusions in a subsequent article of other authors [57] reporting data obtained from an alloy with a Mn concentration of 9.2 at%, it turned out that indeed in this type of QC, two magnetically inequivalent Mn sites exist. Somewhat later this view was supported by theoretical modelling [58]. The majority of the Mn moments are quenched and a small minority carries rather large moments, of the order of a few Bohr magnetons. This inequivalence of sites confirms the influence of differences in the local atomic environments; even the formation of Mn clusters providing rather large moments cannot be ruled out. It was then quite surprising that another monodomain quasicrystal with a slightly different chemical composition, $Al_{72.4}Pd_{20.5}Mn_{7.1}$, revealed qualitatively different magnetic features [59]. The already small number of Mn-ions with a non zero moment decreased even more with decreasing temperature below $T_a \sim 20$ K down to 2 K, as was inferred from data of NMR experiments monitoring the line width of the ^{27}Al resonances in a 6 T applied magnetic field. This data indicate a substantial reduction of the transferred Mn local field at the sites of the ^{27}Al nuclei in this temperature regime. In subsequent experiments discussed below, no evidence for a spin-glass formation down to 0.1 K was observed [60].

Naturally we aimed at identifying the cause for this reduction of stable moments. For the two possibilities of either a Kondo-type screening of moments by itinerant electrons or a reduction of the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction by a reduction of the conduction-electron concentration due to a localization of the latter, we found no convincing independent evidence in the available data sets, however [59]. Extending these measurements to temperatures in the sub-1K regime resulted in yet another surprise [60]. The above mentioned line-width reduction below T_a measured again in an external magnetc field of 6 T, was still observed but abruptly terminated at $T_b \sim 2.5$ K, where the line-width value changes back discontinuously to the value established at 20 K with no further variation down to 0.05 K (see fig. 10) .This latter feature was found to disappear in lower external magnetic fields of the order of 2.5 T or less. At the time we found no convincing explanation for these very unusual phenomena and I believe this is still the case today. Neither is it known why the relatively small variation of 2% of the Mn concentration causes the observed changes in the magnetic properties of these QC series.

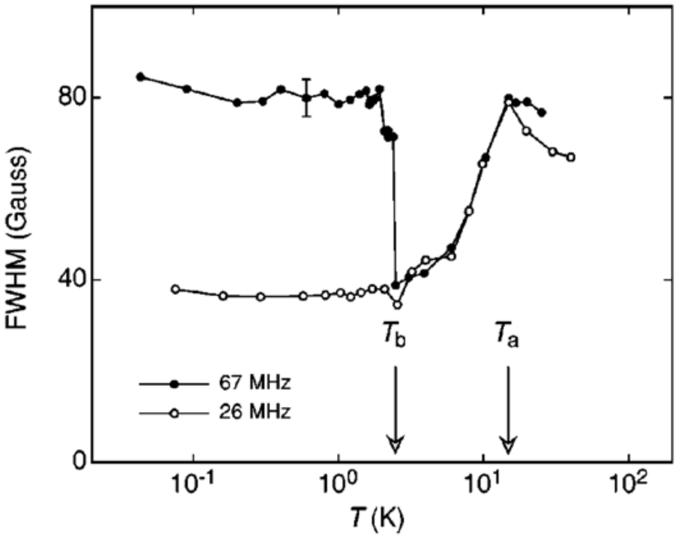

Fig. 10: ^{27}Al NMR line width of a single-grain sample of quasicrystalline $Al_{72.4}Pd_{20.5}Mn_{7.1}$, as a function of temperature, measured in two different external magnetic fields. The solid lines are to guide the eye.

Finally we also made use of the fact that quasicrystalline alloys with identical chemical composition may adopt two different stable quasicrystalline configurations, depending on the samples' thermal treatment. One such example is the alloy $Al_{69.8}Pd_{12.1}Mn_{18.1}$ which is stable with both the icosahedral (i) and the decagonal (d) quasicrystalline configuration [61]. The experiments aimed at comparing the stability of the magnetic moments of the Mn ions in both the quoted materials, again employing ^{27}Al NMR as the probing method, complemented by measurements of the magnetic susceptibility, the electrical resistivity and the specific heat below room temperature [62, 63]. It turned out that in both cases, the magnetic ground state is of spin-glass type with freezing temperatures of $T_f^{ico} = 19$ K and $T_f^{dec} = 12$ K, respectively. The degree of frustration appears to be higher in the decagonal QC. In the icosahedral QC all the Mn ions carry a magnetic moment whereas in the decagonal variety this is true for only about half of them.

Inspecting the plots of the ^{27}Al NMR signal of the d-QC we found two distinct lines which directly indicate the inequivalence of the corresponding Al sites and their Mn environment. Because of considerable line broadening this separation was not possible for the i-variety QC. The spectrum for the d-version, however, consists of a narrow line (I) and a distinctly broader line (II) which may easily be distinguished. The most surprising result obtained in this context is the very anomalous temperature dependence of the spin-lattice relaxation rate $T_1^{-1}(T)$ of line I, i.e., the distinct and magnetic field independent anomalous hump between 175 and 50 K shown in figure 11 [62]. With selected area electron diffraction (SAED) we verified that no structural changes occur between room temperature and 30 K. We conjectured that the unexpected feature is a consequence of the reduction of magnetic moments upon decreasing temperature as outlined above. This feature, often observed for the QC considered here, is admittedly not well understood. Indeed, the evidence of this moment quenching with decreasing temperature in the d-variety of $Al_{69.8}Pd_{12.1}Mn_{18.1}$ is absent in the icosahedral quasicrystalline configuration.

In summary, the bulk of experimetal magnetic data suggests that the stability of Mn-related magnetic moments in these QC depends crucially on both their position in the quasicrystalline lattice and the related local density of d-electron states at the Fermi energy $D_d(E_F)$ [58].

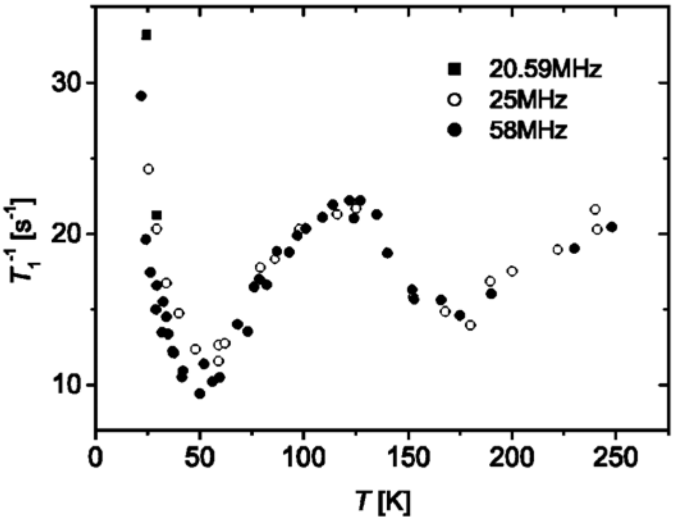

Fig. 11: Spin-lattice relaxation rate $T_1^{-1}(T)$ for the narrow line I of the NMR spectrum of the d-version of $Al_{69.8}Pd_{12.1}Mn_{18.1}$ between 25 and 250 K (see text).

IV. Summary

Summarizing this chapter it may be stated that quasicrystallinity is an established alternative form of matter in the solid state whose structural characteristics require a broader view on crystallography by considering lattices that are periodic in higher dimensions. Quasicrystals are mostly alloys with structure-induced poor metallicity. Details of the electronic transport, especially at low temperatures and in high magnetic fields are not well understood. This deficit may well be traced back to the fact that $k_F \cdot l < 1$ and thus the use of the familiar theoretical concepts is not appropriate. The electronic properties are influenced by critical electronic states which are localized in k-space, strictly different from the delocalized Bloch states in common metals with periodic lattice structures. Similarly, the physics of the lattice involves itinerant and local lattice excitations, termed phonons and phasons. The excitation spectrum of the phonons is characterized by a large number of gaps which requires a new approach to Umklapp processes that govern the characteristics of the thermal conductivity. With respect to lattice statics, experiments have revealed that (i) the compressibility is highly isotropic in icosahedral QC and (ii) transversally isotropic in decagonal QC, both as expected by considering the number of independent elastic constants. The influence of phasons, local, i.e., confined to a spatially limited range, low-energy excitations, possibly in the form of quantum tunneling, dominates the lattice dynamics at very low temperatures. It exhibits features that are not typical for common crystalline materials. Magnetic properties are clearly influenced by the non-periodicity of the lattice and the intrinsic distribution of lattice sites of potentially magnetic ions. The experimentally verified reduction of the number of stable magnetic moments is not well understood.

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For editorial reasons this article is split in two parts. Part 2 will appear in the next issue of the *SPG Mitteilungen*.

Pre-announcement:
Symposium "125th anniversary of George Lemaître"

On the occasion of George Lemaître's 125th anniversary, the Swiss Physical Society is organizing a Symposium on this important figure and the discovery of the expanding Universe. The symposium will be held at the Kuppelsaal of the **University of Bern** on the afternoon of Thursday, **21 November 2019**.

We have invited three eminent speakers bringing in complementary aspects from each of their specific field and expertise.

- Prof. Dr. **Harry Nussbaumer**, ETHZ, will speak on the astronomical environment of the 1920s,
- Prof. Dr. **Jean-Pierre Luminet**, Directeur de recherches au C.N.R.S., Laboratoire d'Astrophysique de Marseille, will address the philosophical aspects and implications of Lemaître's contributions to modern cosmology, and
- Prof. Dr. **Norbert Straumann**, University of Zurich, will speak on "*On Lemaître's inhomogeneous cosmological model of 1933 and its recent revival*". His talk will take the perspective of Einstein's General Theory of Relativity.

Each talk will last 45 minutes and be followed by another 15 minutes of discussion.

Reserve already the date ! A more detailed announcement will follow in time.

Organizer: Prof. Dr. Claus Beisbart, University of Bern and SPS section head: "History and Philosophy of Physics".

History of Physics (23)

SOHO – the ESA / NASA Solar and Heliospheric Observatory
II. The Corona, Coronal Holes and the Solar Wind

Martin C. E. Huber

In part I of this article [1] we introduced SOHO, a spacecraft observing the Sun from L1, the first Lagrange point of the Sun-Earth system, since March 1996, and discussed the first of the three grand goals of the SOHO mission, namely ‘exploring the structure and dynamics of the solar interior’. This is done by the method of helioseismology, which relies on measuring solar oscillations. SOHO’s data resulted in the most detailed and precise measurements of temperature, rotation, and gas flows in the solar interior.

The first part further contained a description of the spacecraft and the twelve, partially complementary instruments that form SOHO’s science payload. These instruments – provided by consortia of investigators in Universities and Research Organisations both in Europe and the U.S. – are being deployed to study the Sun from space in a jointly agreed observing programme, whose data are accessible from the SOHO Archive [2].

The present second part of the article addresses the two other grand scientific goals of SOHO, namely

- ‘why the solar corona exists and how it is heated to a temperature of millions of kelvin’, and
- ‘where and how the solar wind is accelerated’.

Mission Status

It is expected that SOHO operations will eventually be extended for a period of six years from now, to support NASA’s ‘Parker Solar Probe’ [3]. This mission, launched in August 2018, already had a first close fly-by at the Sun. SOHO’s Large Angle and Spectrometric Coronagraph LASCO, in particular, will take images of the solar corona over a field of view extending to 30 solar radii, while the Parker Solar Probe will go through four annual perihelia and probe the corona *in-situ*. At the last perihelia scheduled for 2024 and 2025 the Parker Solar Probe will approach the Sun within a distance of ca. 9.5 solar radii above the photosphere, its perceived ‘surface’!

Some of SOHO’s instruments are still observing regularly; others, which had been turned off earlier in the mission, were turned on occasionally for specific observing campaigns (such as the observations of the perihelion of Comet ISON in December 2012) [4].

The performance of the SOHO spacecraft and its instruments over the now nearly 23 years of observations has been perfect – except for the dramatic, but fortunately only temporary loss of contact in June 1998 (cf. box **III**).

I. The Discovery of the million-kelvin Temperature of the Solar Corona in 1942

Total solar eclipses have startled humans for millennia wherever they occurred. After astronomers were able to predict the place and time of a total eclipse, the scare among the general population began to fade. For astronomers the enigma of the ‘corona’ (‘Strahlenkranz’) surrounding the occulted solar disk remained. After the view that the corona was part of the Sun (rather than an optical artefact) had taken hold early in the 18th century, a new riddle appeared as of 1869, when spectral lines observed in the corona during total solar eclipses could not be assigned to any known chemical element!

In 1942 the Swedish physicist Bengt Edlén showed conclusively that the wavelengths of these ‘unknown’ lines actually corresponded to forbidden transitions between levels of the ground configurations of highly ionised atoms – mainly of iron, nickel and calcium. From the ionisation stages in question Edlén established that coronal temperatures must be of order 10^6 K [1-3].

Exploring the Corona and the Solar Wind

As described in box **I** the mystery of a corona surrounding the Sun was lifted only in 1942 after Bengt Edlén had shown that the emission lines observed in the corona were produced by highly ionised ions, and that the corona‘s temperature therefore was of order 10^6 K.

The existence of a million-degree plasma above the much cooler photosphere presents a riddle though: what is heating the corona? Normally, one would expect a steadily decreasing temperature of any plasma or gas residing above the photosphere. But given the high temperature of the corona one must assume that non-thermal energy is somehow transported to, and deposited at greater height, where it is converted into heat that is carried away by radiation and by thermal conduction to the cooler, lower-lying parts of the atmosphere, or is used to accelerate the solar wind.

In box **II** we summarise how the temperature and density structure of the plasma in the outer solar atmosphere is derived from its extreme-ultraviolet spectrum. This spectrum contains emission lines of many ionisation stages of the more abundant chemical elements. With increasing height higher ionisation stages of a given element are present.

The solar atmosphere lying above the photosphere is traditionally subdivided into three regions, namely the ‘chromosphere’, ‘transition region’ and ‘corona’. An average course of temperature and density in atmospheric layers starting at temperatures occurring within, and then above the photosphere is shown in Fig. 3a of box **II**.

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[1] See *SPG Mitteilungen* Nr. 56:34-37 (2018)

[2] http://sci.esa.int/soho/45900-esa-s-new-soho-science-archive-now-online/

[3] https://en.wikipedia.org/wiki/Parker_Solar_Probe

[4] cf. ‘SOHO the Comet Finder’ at the end of the first part of this article [*SPG Mitteilungen* Nr. 56:34-37 (2018)].

Because the solar atmosphere is inhomogeneous plasma, a proper investigation of the outer solar atmosphere requires observations not only of the spectrum, but also of so-called spectroheliograms, i.e. monochromatic images of the atmosphere – and this over an extended time. Furthermore, as the outer atmosphere shows a rather dynamic behaviour (and sometimes – such as by flaring – even exhibits violent events) a movie-like coverage is of importance as well. Stabilised space platforms that made such observations possible became available in the 1960s [5].

A definitive verdict about the processes that heat the corona and accelerate of the solar wind – the two remaining grand scientific goals of SOHO – cannot be rendered yet. Rather than now presenting a tedious list of plasma processes that have been shown to potentially contribute to heating the corona and/or accelerate the solar wind, we prefer to illustrate now how satellite platforms in space have helped to make progress in investigating a prominent coronal phenomenon, namely coronal holes [6].

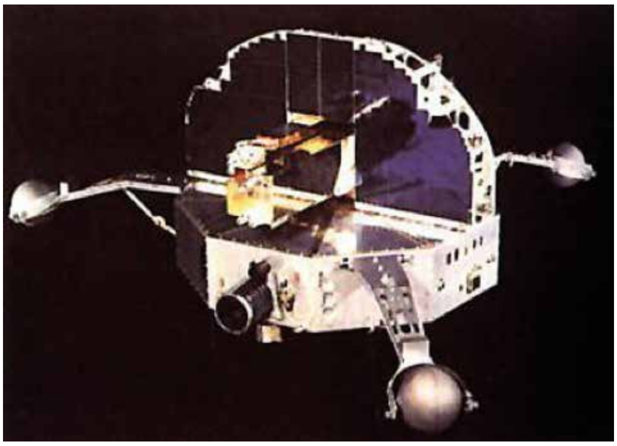

Fig. 1 — NASA's Orbiting Observatory OSO-6. The spacecraft consisted of a rotating 'wheel' providing gyroscopic stability and a 'sail' that contained solar cells for electricity generation and also held two pointed instruments. During the daylight portion of the orbit [7] an electric motor drove the 'sail' relative to the 'wheel' and kept the solar cells in sunlight. By slightly varying its speed, that same motor could also induce an azimuthal scan of two pointed instruments. Together with a second motor that controlled the elevation, one could command the telescope axes of the pointed instruments to perform a raster pattern [8] and thus to cover an extended field of view. [9] (Image: Ball Brothers Research Corporation.)

Coronal holes have been in the focus of solar space research for decades. From correlating observations of coronal holes on the solar disk and successive solar-wind observations near the Earth, it had been inferred that coronal holes might be the source of fast solar wind streams – a supposition that later was confirmed (cf. Fig. 8).

Magnetic field lines coming out of a coronal hole are open, in contrast to magnetic field lines above the adjacent quiet corona, which are generally closed (cf. Fig. 4). As a consequence, it turns out that the shape and position of the temperature curve of the 'quiet' atmosphere shown in Fig. 3b is modified inside a coronal hole.

The Story of Coronal Holes – Progress in the Course of three Space Missions

Our understanding of the properties of coronal holes has benefitted from increasingly sophisticated observing techniques employed by use of three major solar space observatories, namely the two NASA missions OSO-6 and Apollo Telescope Mount (ATM) on Skylab, as well as the joint ESA/NASA SOHO [10]. The scientists involved have also changed their behaviour – along with the technical advances: they introduced joint observing planning and increased the collaboration between the instrument teams along with instituting a policy of open data access that eventually led to freely accessible archives containing the collected calibrated data [11].

1. OSO-6 — the sixth Orbiting Solar Observatory

The OSO-6 satellite, launched in August 1969 and shown in Fig. 1, contained two pointed instruments, one of which was the spectroheliometer to be discussed here [6]. A spectroheliometer is a telescope-spectrometer combination for solar observations that is equipped with a photoelectric detector. In the telescope's focus there is a spectrometer 'slit'. In the instrument in question this 'slit' was a 35" x 35" [12] aperture, and the spectrometer was able to scan a wavelength range between 28.5 nm and 138.5 nm, chosen to study the solar chromosphere, transition region and corona.

The two basic modes of a spectroheliometer are, (i), generating a monochromatic image by scanning the telescope axis over the Sun with the spectrometer set to a fixed wavelength and, (ii), recording the spectrum of a specific point on the Sun by obtaining a wave-length scan with a fixed telescope pointing. The OSO-6 satellite provided the articulation of the telescope axis for both these modes: based on commands from the ground it pointed the telescope axis to any position within a 45' x 45' field of view (FOV) centred on the Sun [13], or it performed a raster scan over any desired area within the FOV.

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[5] We recall that the first solar spectra photographed above the ozone layer by a spectrograph mounted on a rocket were obtained in 1946 [4]. Hard work over more than a decade then was needed to develop stabilised satellite platforms with tape recorders that could perform the required measurements [5].

[6] … often jokingly referred to as the second-most interesting kind of hole in astronomy.

[7] OSO-6 was in a near-circular orbit at 530 km altitude with a 90-min period and 33° inclination. During its orbit the satellite was in daylight for 60 min and spent the remaining 30 min behind the Earth.

[8] …OSO's pointing system performed the raster scan mechanically in a boustrophedonic pattern (so named after oxen plowing a field): there is a turn after each 'line' in the pattern, and no retrace to the beginning of the next line, as 'raster' usually implies.

[9] In its 'wheel' OSO-6 also carried instruments that saw the Sun every 2 s. Some of these instruments observed the Sun, others had been designed to observe non-solar objects in the sky. A slow roll of the spacecraft about the line of sight to the Sun provided the instruments in the wheel with access to the entire celestial sphere over six months.

[10] The choice is suitable, but not impartial; the author participated in preparing and calibrating instruments that obtained the observations to be discussed; the first two while working at Harvard College Observatory in Cambridge MA/USA, the third one after he had returned to Europe to work at ETHZ and ESA.

[11] Note that these three space observatories easily cover half a century, if one includes the time for pre-launch preparations, operation, and data interpretation. A change in social behaviour may therefore be expected.

[12] The symbols ' and " are used for arc minute and arc second, respectively.

[13] As the solar disk has a diameter of ca. 32', the field of view extended well into the corona.

II. From the EUV-Spectrum of the Sun to the Structure of its Outer Atmosphere.

The extreme-ultraviolet (EUV) spectrum of the Sun (Fig. 2) is an emission spectrum – quite in contrast to the visible solar spectrum that we know from textbooks, where a colourful stretch of continuum radiation is interspersed with dark Fraunhofer lines (which indicate the presence of a given element in the Sun, and can be used to determine the solar abundance of the chemical elements).

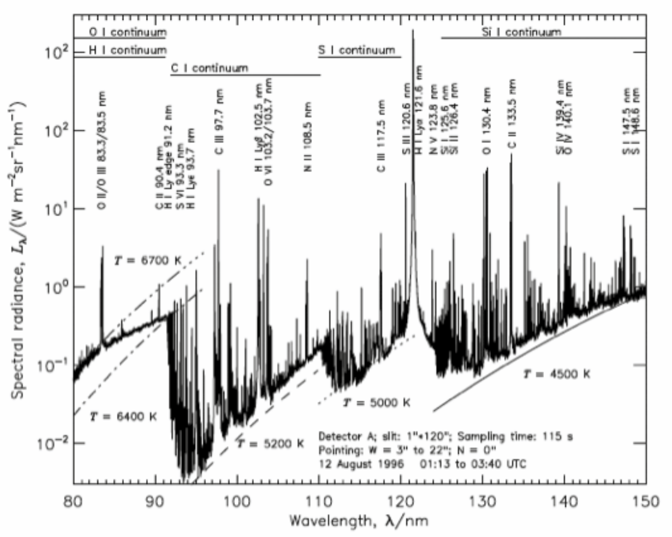

Fig. 2 — The outer solar atmosphere reveals its structure through the extreme-ultraviolet (EUV) spectrum. This spectrum, recorded by the SUMER instrument on SOHO, contains mainly emission lines [14]. The spectral resolution of SUMER also provides information on line profiles and Doppler shifts; its information content thus exceeds by far what can be shown in this reproduction [15]. From [7].

Starting from this spectrum one can determine the temperature and density structure of the outer solar atmosphere. The strength of a given emission line in Fig. 2 depends on the abundance of the element in question [16], on the calculated fractional ionisation equilibrium of the ion to which the emission line in question belongs, on atomic parameters as well as on the temperature and density structure of the outer solar atmosphere. In turn, the course of the latter parameters can iteratively be determined from the apparent strengths of the lines observed, provided the spectrum has been obtained by a radiometrically [17] calibrated spectroheliometer like SUMER.

The plot of Fig. 3a renders the course of temperature and density in the outer solar atmosphere – within its subdivisions: chromosphere, transition region and corona.

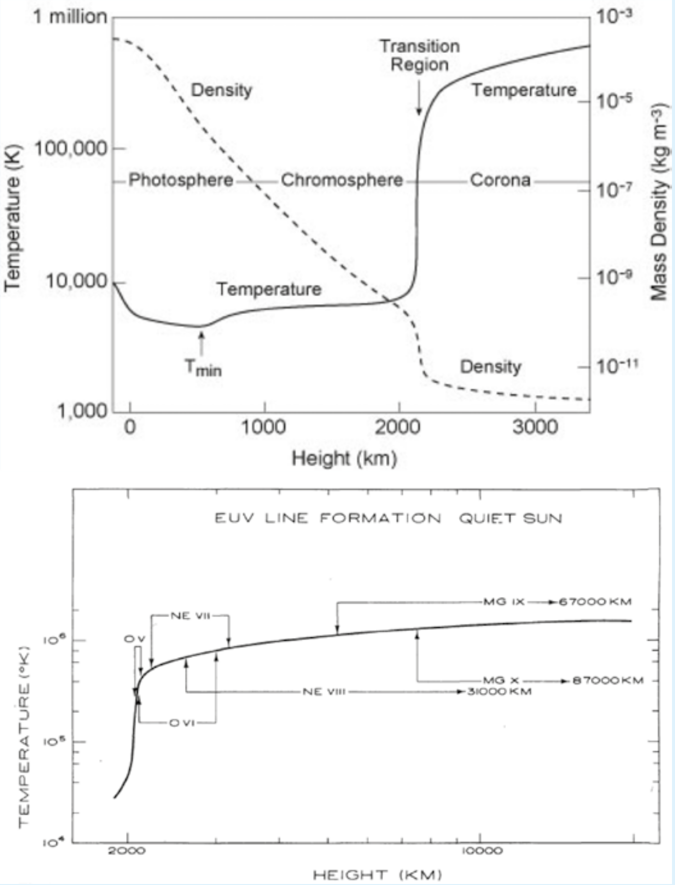

Fig. 3 — a) Top: Temperature, T, and density, ρ, vs height in the outer solar atmosphere (from [8]), b) Bottom: a temperature profile labelled with some ranges of EUV line formation; by the choice of an ion, whose spectral lines one observes, one simultaneously selects the height of the atmospheric feature to be observed (if one assumes a homogeneous plasma). From [9].

Fig. 3b shows the part of the T vs. h model starting at the foot of the transition region that is particularly relevant for deriving the atmospheric structure based on the spectrum of Fig. 2. Temperature (and height) range where a given ion contributes to the radiative output is marked. This presentation assumes a homogeneous atmosphere – a useful initial assumption that is however not realistic. The reason is that the plasma β (i.e. the ratio between plasma and magnetic pressure) is very small in the tenuous plasma of the outer solar atmosphere; the magnetic field therefore strongly determines the geometry of the plasma (cf. Fig. 4).

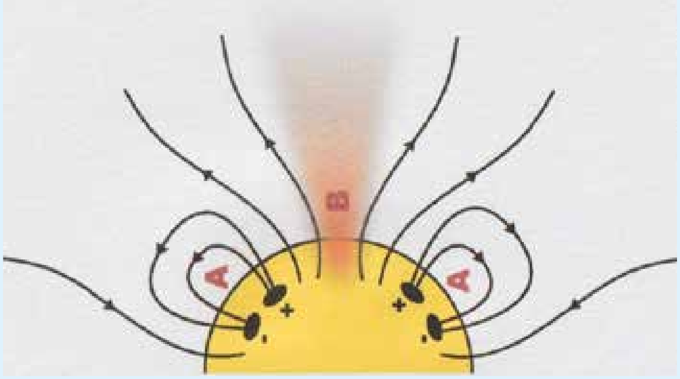

Fig. 4 — Schematic magnetic field lines that could fit the borders of a coronal hole. (Note: to match the orientation of the polar coronal hole in Fig. 7 the picture has been rotated by 90°.)

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[14] Labels identifying the emission lines follow the spectroscopic notation, where the roman numerals indicate the spectrum to which the lines belong. The first spectrum is that of the neutral atom; a line belonging to the second spectrum, such as N II, accordingly is emitted by singly ionised N^{+1}.

[15] On this reproduction a spectral resolution element corresponds to 5 μm.

[16] …which, to start with, is assumed to be the same as that derived from visible spectra of the photosphere.

[17] Rather than ‘photometric’, whose definition is related to human vision, we prefer ‘radiometric’, which relates to measurements of electromagnetic radiation at all wavelengths.

The spectroheliometer on OSO-6 had only one detector – an open magnetic electron multiplier (MEM) with a tungsten cathode [18], where the photoelectron and the secondary electrons were multiplied on a continuous dynode strip. Crossed magnetic and electric fields forced electrons released after each impact back to the dynode strip and carried them along towards the anode, where the arriving electron avalanche triggered a counter [10].

A remarkable aspect of the OSO-6 experiment was its ‘quick-look’ system. Observing at short wavelengths often requires a reaction to changing conditions on the Sun. With OSO-6 it was possible to receive formatted data of the observations in real time (or from a playback of the tape recorder) as long as the satellite was within view of a NASA ground station. The ‘quick-look’ system transmitted data received at the ground station to the Goddard Space Flight Center in Greenbelt MD for data processing and then via a dedicated phone line to a line printer [19] at Harvard College Observatory (HCO) in Cambridge MA. Instrument settings could then be changed in response to a new situation, if necessary.

Normally, solar astronomers at HCO decided in daily meetings on the observing programme for the next 24 to 48 hours. A computer generated the required command sequence that was then transmitted to GSFC by a ‘telecopier’ [20]. Note that this was a system operating in 1969 – two decades before the the World Wide Web became a reality! [11]

In order to draw quantitative conclusions from the EUV radiation received, the instrument’s absolute responsivity had been determined in the laboratory before launch; but it was soon noted that the (absolute and wavelength-dependent) responsivity changed in space.

After eight months, when the loss had reached a factor of twenty it was decided to cease observing with OSO-6. The drop of responsivity was probably caused by a combination of loss of the reflectivity of the telescope mirror and loss of detector efficiency – both the consequence of molecular contamination [21].

The OSO-6 spectroheliogram in Fig. 5 shows a coronal hole.

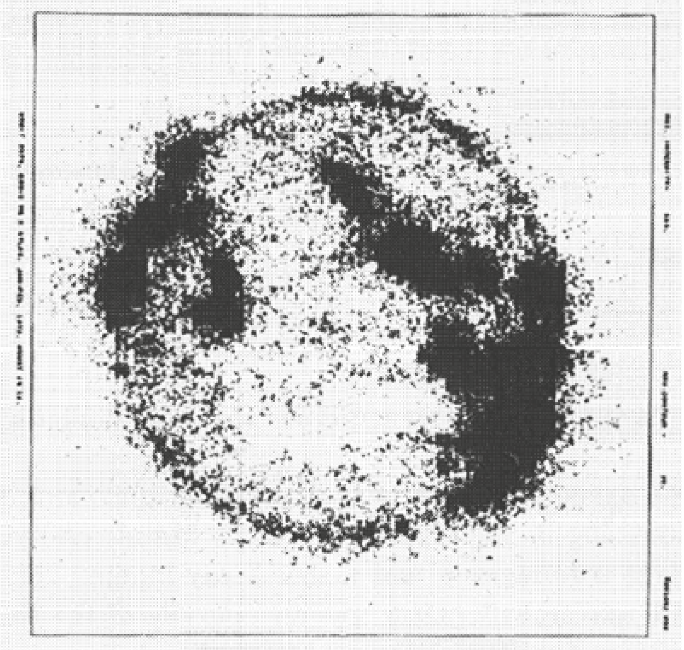

Fig. 5 — A coronal hole seen in a full-field spectroheliogram recorded with the OSO-6 spectroheliometer set to the Mg X line at $\lambda = 62.5$ nm – a line emitted by 9-times ionised magnesium. The radiation observed stems from coronal plasma with $T \approx 1$ MK, and thus visualises the corona. In the coronal hole the temperature does not reach 10^6 K, thus there appears a hole. Note that thanks to the solar-blind detector, the corona can here be seen in front of the solar disk. This original image was chosen to show the rather rudimentary state of image presentation of the early 1970s. (Image from [12])

2. The Apollo Telescope Mount (ATM) on Skylab

Skylab (shown in Fig. 6) was a space station built with hardware left over from the Apollo Moon missions, and was launched by a Saturn-V rocket in May 1973. Three crews, each composed of three astronauts, were launched in Apol-

Fig. 6 — The Skylab space station, consisting of an ‘Orbital Workshop’ (visible below the yellow ‘parasol’), which provided living and working space for the astronauts, and of the Apollo Telescope Mount (ATM). The front ends of the eight solar telescopes in the ATM can be seen inside the white rim framed by four solar panels. Joint daily observing programmes for all instruments were devised on the ground by a group of solar physicists representing all the investigator groups and were then transmitted to the astronauts on Skylab for execution – with the proviso that unexpected behaviour of the Sun might lead to improvised changes to be decided by the astronaut-observer on duty. The ‘parasol’ covering the ‘orbital workshop’ had to be installed by the first crew arriving at Skylab, because the so-called micro-meteorite shield of the workshop, which also would have provided thermal insulation, was lost during the launch of Skylab and also led to the loss of what would have been an additional solar panel on the left side of the orbital workshop. (Image taken by the third Skylab crew, Credit: NASA.)

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[18] A tungsten cathode is insensitive to any remaining stray-light caused by the overwhelming visible and near-ultraviolet photospheric radiation, because its work function exceeds by far the energy of photons at the wavelengths in question. Such cathodes are called ‚solar-blind’

[19] Spectroheliograms could be visualised on a line printer by making use of print characters with different amounts of ink and by overprinting lines.

[20] An early kind of fax machine.

[21] Assembling and testing of the spectroheliometer for the OSO-6 mission as well as launch preparations took place in cleanrooms, of course. However, the cleanliness specifications at that time were numerically defined only for particulate contamination. Later it was realised that molecular contamination of optical elements can lead to polymerisation and subsequent loss of reflectivity upon exposure to extreme ultraviolet radiation in space. For the later SOHO mission the builders of the spacecraft used a cleanliness requirement of a few hundred ng/cm^2 of condensable and particulate contamination, and the instrument teams aimed for even less. A more stable responsivity in orbit was achieved in this way (cf. [13]).

lo Command and Service Modules (CSM) on Saturn-IB rockets to visit Skylab, where they docked their CSMs. At the end of their visits they entered into the CSM and used it for their return to Earth. The first crew spent a month on Skylab, the second and third crews two and three months, respectively.

All the solar telescopes in the ATM had internal pointing capabilities, and most used photographic film. Only the Harvard spectroheliometer had photoelectric detectors. Use of film was possible on Skylab: the astronauts brought the exposed film back to Earth for developing and subsequent use in research. A definite advantage was that the astronaut observing the Sun could immediately respond to unexpected events occurring on the Sun.

Fig. 7 shows Skylab observations of a coronal hole on the solar limb. We deduce that the temperature gradient within the coronal hole is less steep than in what usually is called the 'quiet' outer solar atmosphere. Note also that both the spatial resolution of Skylab observations (pixel-size: 5" x 5") and the visualisation have improved as compared to the OSO-6 spectroheliogram shown in figure 5.

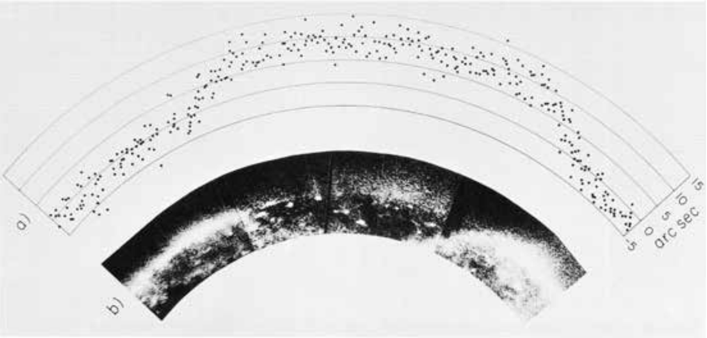

Fig. 7 — An example of Skylab observations. In panel a) a plot of the height of the limb over the south pole of the Sun, as seen in the Ne VII line at $\lambda = 46.5$ nm (whose temperature of formation is $T_f \approx 7 \times 10^5$ K) beyond the limb formed by the radiation of the Lyman continuum (with $T_f \approx 10^4$ K). From the separation of the apparent limbs corresponding to the two temperature indicators Ne VII and Lyman continuum, one concludes that the temperature gradient inside a coronal hole is more gradual than that observed outside coronal holes: the strong rise of temperature shown in Fig. 3b of Box II is more gentle inside a coronal hole and owing to the absence of radiation of Mg X (as evident from panel b) the temperature reaches a plateau below $T_f \approx 10^6$ K. Panel b) is a representation of a set of spectroheliograms photo-electrically recorded in the Mg X $\lambda = 62.5$ nm line ($T_f \approx 10^6$ K) that show the extent of the coronal hole near the pole. (From [14]).

3. SOHO Observation of the Solar-Wind Speed in an Area Covered by a Coronal Hole

The SUMER instrument on SOHO used imaging photon counters – a major advantage over the OSO-6 and Skylab instruments that had only, respectively, one and seven photon counters. With its considerably improved spatial resolution of ca. 1" and a spectral resolution that permitted measuring Doppler shifts [22], SUMER thus could observe Dopplergrams that cover an extended field of view and, as seen in Fig. 8, confirm that coronal holes indeed act as a source of fast solar-wind streams.

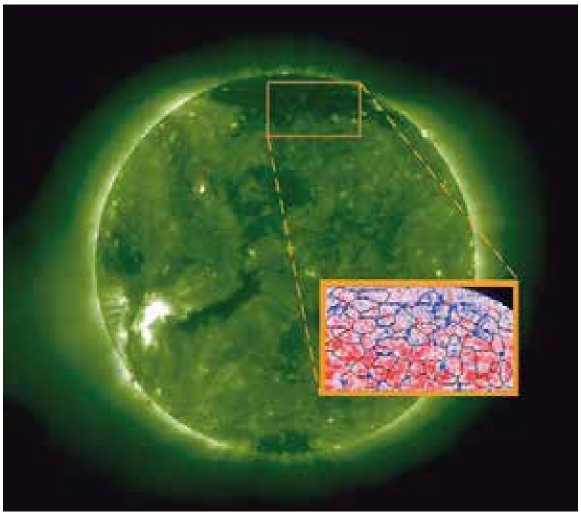

Fig. 8 — Coronal holes are source regions of fast solar wind. Spectral lines observed in an area covered by a coronal hole exhibit a blueshift, while redshifts prevail in the surrounding quiet solar atmosphere. Dark borders marked on the Dopplergram are boundaries of so-called magnetic network cells. This phenomenon, which was known from EUV observations by ATM, shows the influence of the magnetic field on a smaller scale than with the overall boundary of a coronal hole. ATM observations had also shown that the boundary of a coronal hole coincides at low altitude with boundaries of network cells. Background: solar image taken by SOHO's Extreme Ultraviolet Telescope (EIT) around $\lambda = 19.5$ nm, representing solar plasma at $T \approx 1.6$ MK. (From [15]).

Dynamic Events in the Corona: Mass Ejections that Propagate into the Heliosphere

SOHO also provided much information on the dynamics of the upper solar atmosphere. This may best be illustrated by movies taken by the Large Angle Solar Coronagraph (LASCO) instrument on SOHO. Coronal Mass Ejections (CME) had already been regularly studied by use of photographs taken by the coronagraph flown on board of Skylab, but the improved image quality and the wide field out to 30 solar radii, as well as the faster image cadence recorded by the charge-coupled devices (CCD) on SOHO's LASCO, keep extending our knowledge about these energetic events that disturb the heliosphere [23].

A coronal transient traveling directly toward the Earth will perturb the terrestrial plasma environment, and influence what has become known as 'space weather'. In the worst case satellite failures might result, and power surges in installations on the ground could occur. SOHO thus also helps to forecast the space weather in the Earth's environment.

Conclusion

As the jury is still out regarding a definitive judgment on the panoply of candidate processes envisaged for heating the corona and/or accelerating the solar wind, we preferred to demonstrate how our knowledge of a specific topic, namely 'coronal holes and the fast solar wind stemming from them' has increased by use of advanced instrumentation. Studies of coronal heating will require observations with even higher spatial, spectral and time resolution than those available on SOHO [16].

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[22] Note the remark in the caption of Fig. 2 of box II: "The spectral resolution of SUMER also provides information on line profiles and Doppler shifts …"

[23] http://www.esa.int/spaceinvideos/Videos/2017/09/SOHO_s_view_of_September_solar_flares

III. «Lost in Space» – SOHO's Recovery and then the first Gyro-less 3-Axis Stabilised Spacecraft!

"The SOHO mission almost ended on 25 June 1998 when control was lost during a routine spacecraft manoeuvre." and "The space scientist's and space engineer's worst nightmare was beginning to unfold – SOHO was lost in space!" – detailed reports about this event [17, 18] start with such gloomy sentences. Indeed, after loss of contact the spacecraft was spinning, lost electrical power and was no longer pointing at the Sun. ESA experts immediately travelled to the US to support the local operations personnel at the SOHO Operations Center in Greenbelt MD.

On 23 July researchers from the US National Astronomy and Ionosphere Center (NAIC) offered to employ bi-static radar, with the 305-meter diameter dish of the Arecibo radio telescope in Puerto Rico transmitting radar pulses towards SOHO and the 70-m dish of NASA's Deep Space Network in Goldstone (CA/USA) receiving the echo. On the next day, the spacecraft was located! The radar echoes confirmed SOHO's predicted location and revealed a spin rate of about 1 rpm.

A carrier signal from SOHO was then detected on August 3. This meant that the spacecraft's battery was being charged again; and when telemetry was received on August 8 the recovery of SOHO could commence.

The first tasks now were to allocate the limited electrical power available and to determine SOHO's anomalous orientation in space. On August 12, the thermal control heaters of SOHO could be switched on in order to start the thawing of the frozen hydrazine fuel tank; thawing pipes and thrusters then followed. Now SOHO could be re-oriented towards the Sun. Further recovery activities concerning the spacecraft-bus then took place and after an orbital correction manoeuvre on September 25, the SOHO spacecraft was in its normal mode again.

Recovery of the instruments took place between October 5 and 24, 1998. All instruments could be re-commissioned, although they had seen temperature extremes from below -120 °C to +100 °C. Some instruments were found to have an improved performance – contamination on mirrors and detectors had apparently evaporated during the hot periods.

SOHO was back in service now, but further trouble was still in store: two of the three gyro units that could provide attitude control had not survived the period when SOHO was out of control. The third gyro did fail on December 21. Attitude could still be maintained by manual thruster firings, but this procedure consumed fuel at a rate of 7 kg per week. ESA therefore accelerated the development of software for a new gyro-less operation that had been started when the failure of the other two gyros was known. And on February 1, 1999, after the new software was installed, SOHO became the first 3-axis stabilised spacecraft without gyroscopes!

ESA is currently preparing the Solar Orbiter mission for launch in 2020. Its spacecraft will explore the inner heliosphere by following a trajectory bringing it within only 0.3 AU from the Sun, and eventually up to solar latitudes around 25°. The latter will facilitate investigations of the atmosphere near the pole of the Sun.

The Solar Orbiter payload combines remote sensing with *in-situ* analysis of the environment. The mission's overarching goal is to find an answer to the question: How does the Sun create and control the heliosphere?

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History of Physics (24)

Hermann Weyl's Space-Time Geometry and the Origin of Gauge Theory 100 Years ago

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One of the major developments of twentieth century physics has been the gradual recognition that a common feature of the known fundamental interactions is their gauge structure. In this contribution the early history of gauge theory is reviewed, emphasizing mainly Hermann Weyl's seminal contributions of 1918 and 1929. Wolfgang Pauli's remarkable early construction in 1953 of a non-Abelian Kaluza-Klein theory is mentioned in more detail in an extended version of this article, which will be available on the SPS webpage (*https://www.sps.ch/fileadmin/articles-pdf/2019/Mitteilungen_History_24_ext.pdf*).

1 The Quest for Unification

After Einstein had reached his goal of a successful relativistic theory of gravity, he began to think about the remaining arbitrariness of the new theoretical framework. One of these was the separate existence of gravitation and electromagnetism. According to his views, they had to be unified.

A first very interesting unification attempt was put forward by another great figure, namely Hermann Weyl. Before we come to this, it should be said, that before GR was born Weyl was occupied with central problems in pure mathematics. But with Einstein's new theory of gravity he became very interested in general relativity. He wrote the first systematic presentation of the theory with the title "Space-Time-Matter" (STM) [4], after his lectures on the subject in the Summer Term of 1917 at ETH in Zürich.

Figure 1: Hermann Weyl.

In this contribution we first sketch in a non-technical manner [1] Hermann Weyl's early attempt to unify gravitation and electromagnetism by extending the space-time structure of general relativity (GR). Einstein admired Weyl's theory as "*a coup of genius of the first rate* ...", but immediately realized that it was physically untenable: "*Although your idea is so beautiful, I have to declare frankly that, in my opinion, it is impossible that the theory corresponds to nature.*" This led to an intense exchange of letters between Einstein (in Berlin) and Weyl (at the ETH in Zürich), which is now published in The Collected Papers of Einstein [1]. No agreement was reached, but Einstein's intuition proved to be right.

Although Weyl's attempt was a failure as a physical theory it paved the way for the correct understanding of what is called gauge invariance, a central symmetry principle of modern physics. Weyl himself re-interpreted his original theory after the advent of quantum theory in a seminal paper [2].

2 Weyl's Attempt to unify Gravitation and Electromagnetism

On the 1st of March 1918 Weyl writes in a letter to Einstein: "*These days I succeeded, as I believe, to derive electricity and gravitation from a common source ...*". Einstein's prompt reaction by postcard indicates already a physical objection which he explained in detail shortly afterwards. Before we come to this we indicate the main ideas of Weyl's theory of 1918 [3].

2.1 Weyl's Generalization of Riemannian Geometry

Weyl's starting point was purely mathematical. He felt a certain uneasiness about Riemannian geometry [2], as is clearly expressed by the following sentences early in his paper:

> *But in Riemannian geometry described above there is contained a last element of geometry "at a distance" (ferngeometrisches Element) — with no good reason, as far as I can see; it is due only to the accidental development of Riemannian geometry from Euclidean geometry. The metric allows the two magnitudes of two vectors to be compared, not only at the same point, but at any arbitrarily separated points. A true infinitesimal geometry should, however, recognize only a principle for transferring the magnitude of a vector to an infinitesimally close point and then, on transfer to an arbitrary distant point, the integrability of the magnitude of a vector is no more to be expected that the integrability of its direction.*

After these remarks Weyl turns to physical speculation and continues as follows:

> *On the removal of this inconsistency there appears a geometry that, surprisingly, when applied to the world, explains not only the gravitational phenomena but also the electrical. According to the resultant theory both spring from the same source, indeed in general one cannot separate gravitation and electromagnetism in a unique*

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[1] For a more extended version that includes the relevant mathematical aspects we refer to [5].

[2] This is the geometry based on the metric field of GR, that provides the mathematical tools for Einstein's theory of gravity. Einstein learned this (relatively new) mathematics from his friend Marcel Grossmann, who was professor for mathematics at ETH. The two colleagues had from summer 1912 to spring 1914 a very fruitful collaboration, in which they came close to the final theory.

> *manner. In this theory all physical quantities have a world geometrical meaning; the action appears from the beginning as a pure number. It leads to an essentially unique universal law; it even allows us to understand in a certain sense why the world is four-dimensional.*

For certain readers the following few technical explanations may be useful. (A detailed description can be found in [5].) In contrast to GR Weyl's geometry is equipped not with one, but a class $[g]$ of conformally equivalent metrics This corresponds to the requirement that it should only be possible to compare lengths at one and the same world point. In addition, the theory contains also a class of vector fields $[A]$. A crucial property is that substitutions of the form

$$g \to e^{2\lambda} g, \qquad A \to A - d\lambda, \qquad (1)$$

where λ is an arbitrary smooth space-time function, do not change the geometry. Pairs (g, A) related by (1) are considered to be equivalent. In Weyl's application to physics, they leave the physical laws unchanged. These transformations, called *gauge transformations*, play a central role. The first of the substitutions is interpreted by Weyl as a different choice of calibration (or gauge). This is accompanied by the substitution of the vector field A, a transformation physicists know since the 19th century from electrodynamics.

2.2 Electromagnetism and Gravitation

Turning to physics, Weyl assumes that his "purely infinitesimal geometry" describes the structure of space-time and consequently he requires that physical laws should satisfy a double-invariance:

1. They must be invariant with respect to arbitrary smooth coordinate transformations.
2. They must be *gauge invariant*, i.e., invariant with respect to substitutions (1) for an arbitrary smooth function λ.

Nothing is more natural to Weyl, than identifying A with the vector potential and $F = dA$ with the field strength of electromagnetism.

Independent of the precise form of the action Weyl shows that in his theory gauge invariance implies the *conservation of electric charge* in much the same way as general coordinate invariance leads to the conservation of energy and momentum This beautiful connection pleased him particularly: "... [it] seems to me to be the strongest general argument in favour of the present theory — insofar as it is permissible to talk of justification in the context of pure speculation." Similar structural connections hold also in modern gauge theories.

2.3 Einstein's Objection

After this sketch of Weyl's theory we come to Einstein's striking counterargument which he first communicated to Weyl by postcard. The problem is that if the idea of a non-integrable length connection (scale factor) is correct, then the behaviour of clocks would depend on their history. Consider two identical atomic clocks in adjacent world points and bring them along different world trajectories which meet again in adjacent world points. Then their frequencies would generally differ. This is in clear contradiction with empirical evidence, in particular with the existence of stable atomic spectra. Einstein therefore concludes:

> *... (if) one drops the connection of the metric to the measurement of distance and time, then relativity looses all its empirical basis.*

The author has described the intense and instructive subsequent correspondence between Weyl and Einstein elsewhere [6]. As an example, we quote from one of the last letters of Weyl to Einstein:

> *This [insistence] irritates me of course, because experience has proven that one can rely on your intuition; so little convincing your counterarguments seem to me, as I have to admit ...*
>
> *By the way, you should not believe that I was driven to introduce the linear differential form in addition to the quadratic one by physical reasons. I wanted, just to the contrary, to get rid of this 'methodological inconsistency (Inkonsequenz)' which has been a stone of contention to me already much earlier. And then, to my surprise, I realized that it looks as if it might explain electricity. You clap your hands above your head and shout: But physics is not made this way !* (Weyl to Einstein 10.12.1918).

3 Weyl's 1929 Classic: "Electron and Gravitation"

Shortly before his death late in 1955, Weyl wrote for his *Selecta* [7] a postscript to his early attempt in 1918 to construct a 'unified field theory'. There he expressed his deep attachment to the gauge idea and adds (p.192):

> *Later the quantum-theory introduced the Schrödinger-Dirac potential ψ of the electron-positron field; it carried with it an experimentally-based principle of gauge-invariance which guaranteed the conservation of charge, and connected the ψ with the electromagnetic potentials ϕ_i in the same way that my speculative theory had connected the gravitational potentials g_{ik} with the ϕ_i, and measured the ϕ_i in known atomic, rather than unknown cosmological units. I have no doubt but that the correct context for the principle of gauge-invariance is here and not, as I believed in 1918, in the intertwining of electromagnetism and gravity.*

This re-interpretation was developed by Weyl in one of the great papers of the twentieth century [8]. Weyl's classic does not only give a very clear formulation of the gauge principle, but contains, in addition, several other important concepts and results.

Much of Weyl's paper penetrated also into his classic book "The Theory of Groups and Quantum Mechanics" [8]. There he mentions also the transformation of his early gauge-theoretic ideas: "*This principle of gauge invariance is quite analogous to that previously set up by the author, on speculative grounds, in order to arrive at a unified theory of gravitation and electricity. But I now believe that this gauge invariance does not tie together electricity and gravitation, but rather electricity and matter.*"

Many years later, Weyl summarized this early tortuous history of gauge theory in an instructive letter [9] to the Swiss writer and Einstein biographer C. Seelig [9], which we reproduce in an English translation.

> *The first attempt to develop a unified field theory of gravitation and electromagnetism dates to 1918, in which I added the principle of gauge-invariance to that of coordinate invariance. I myself have long since abandoned this theory in favour of its correct interpretation: gauge-invariance as a principle that connects electromagnetism not with gravitation but with the wave-field of the electron. — Einstein was against it [the original theory] from the beginning, and this led to many discussions. I thought that I could answer his concrete objections. In the end he said "Well, Weyl, let us leave it at that! In such a speculative manner, without any guiding physical principle, one cannot make Physics." Today one could say that in this respect we have exchanged our points of view. Einstein believes that in this field [Gravitation and Electromagnetism] the gap between ideas and experience is so wide that only the path of mathematical speculation, whose consequences must, of course, be developed and confronted with experiment, has a chance of success. Meanwhile my own confidence in pure speculation has diminished, and I see a need for a closer connection with quantum-physics experiments, since in my opinion it is not sufficient to unify Electromagnetism and Gravity. The wave-fields of the electron and whatever other irreducible elementary particles may appear must also be included.*

4 On Pauli's Invention of non-Abelian Kaluza- Klein Theory in 1953

There are documents which show that Wolfgang Pauli constructed in 1953 the first consistent generalization of the five-dimensional theory of Kaluza, Klein, Fock and others to a higher dimensional internal space. Because he saw no way to give masses to the gauge bosons, he refrained from publishing his results formally. This is still a largely unknown chapter of the early history of non-Abelian gauge and Kaluza-Klein theories.


Figure 2: W. Pauli around 1956.

Pauli described his detailed attempt of a non-Abelian generalization of Kaluza-Klein theories extensively in some letters to A. Pais, which have been published in Vol. IV, Part II of Pauli's collected letters [10], as well in two seminars in Zürich on November 16 and 23, 1953. The latter have later been written up in Italian by Pauli's pupil P. Gulmanelli [11]. An English translation of these notes by P. Minkowski is now available on his home page. By specialization (independence of spinor fields on internal space) Pauli got all important formulae of Yang and Mills, as he later (Feb. 1954) pointed out in a letter to Yang [12], after a talk of Yang in Princeton. Pauli did not publish his study, because he was convinced that "*one will always obtain vector mesons with rest mass zero*" (Pauli to Pais, 6 Dec., 1953 in [13]).

At a time when Wolfgang Pauli was still a Gymnasium student in Vienna he analyzed observational implications of Weyl's proposed action for the field equations of his new theory. In a technically demanding paper he computed the perihelion motion and the light deflection after he had solved approximately the complicated forth-order field equations for the problem. Pauli showed that Einstein's results are reproduced, however only for a special choice of an additional integration constant, in comparison to GR, which showed up for the higher order field equations.

On 10 May 1919 Hermann Weyl wrote to the 19 year old Pauli (in an English translation):

> *I am extremely pleased to be able to welcome you as a collaborator. However, it is almost inconceivable to me how you could possibly have succeeded at so young an age to get hold of all the means of knowledge and to acquire the liberty of thought that is needed to assimilate the theory of relativity.*

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Nobel Award 2018 in Physics

Chirped-pulse amplification: the technology and its applications

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1. Introduction

Ultrashort pulses of light generated with lasers have enabled a wide range of applications during the past decades. In the visible to near-infrared spectral region, these electromagnetic wavepackets have durations in the picosecond to femtosecond range. Besides their short duration, which enables time-resolved measurements of some of the fastest physical and chemical processes, many applications are based on the fact that very high peak power and intensity can be reached with moderate amounts of energy per pulse. A typical ultrafast laser oscillator emits pulses with an energy of several nJ and peak power approaching a MW. State-of-the-art values exceed these typical numbers by orders of magnitude [1, 2]. By sending the beam through additional optical amplifier stages, pulse energies can be raised to many J, with peak power and intensity scaling accordingly. A MW-peak-power pulse focused to a spot size of 10 μm^2 yields a peak electric-field strength approaching 10 GV/m. The easily accessible high light intensities give rise to a multitude of nonlinear optical interactions that were out of reach with traditional light sources. These light pulses can break chemical bonds, which is a property that is used for precise, non-thermal machining of a wide range of materials, including transparent or heat-sensitive compounds. However, it is exactly these attractive properties that was hindering progress in developing sources of intense ultrashort laser pulses for a long time. While nonlinear optical interaction or the processing of materials is desired in many applications, it was a major challenge to prevent these effects from occurring where they were entirely unwanted: within the laser system itself.

One half of the 2018 Nobel Prize in Physics was awarded to Donna Strickland and Gérard Mourou for the invention of the chirped-pulse amplification (CPA) technique [3, 4]. CPA was a technological breakthrough that addressed the above problem and enabled new generations of ultrashort pulse amplifiers that produce laser pulses with many orders of magnitude higher peak power and intensity than what was previously considered possible.

2. Ultrashort pulse propagation

To understand the operation principle of CPA and the motivation behind it, we first need to understand how ultrashort optical pulses propagate through materials. We will limit the discussion to media with negligible absorption in the optical frequency range covered by the pulse, which is a reasonable assumption for the typical optical components being used inside a laser system.

The Fourier-relationship between time and frequency implies that a short pulse in time domain must exhibit a broad spectral power distribution in frequency domain. In this Fourier picture, an ultrashort optical pulse is a superposition of monochromatic (i.e., single-frequency) waves covering a wide range of different frequencies (Fig. 1a). If all of these monochromatic waves add up in phase, the resulting pulse is the shortest for a given spectral power distribution.

The propagation of monochromatic waves is governed by the refractive index of a material. In any material other than vacuum the refractive index is a function of frequency. The presence of such dispersion immediately implies that if the constituent frequencies were in phase at the input of a block of material, then this will in general not be the case anymore at its output (Fig. 1b). The resulting output pulse will thus be longer than the initial pulse. The shorter the initial pulse, the broader its frequency spectrum, the more the refractive index will vary across the pulse spectrum for a given material. Shorter pulses are therefore affected more strongly by dispersive pulse broadening than the more narrowband longer ones. This is illustrated for propagation through a typical optical material in Figure 1c.

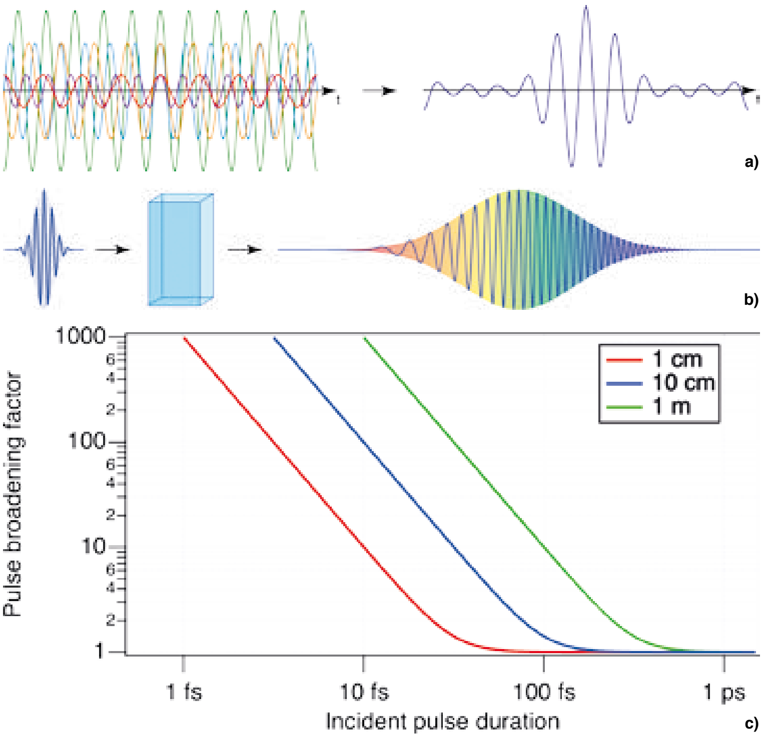


Figure 1: Ultrashort optical pulses. a) A superposition of five monochromatic waves with different frequencies (left) leads to short wavepacket of light (right). Superimposing a broad continuum of frequencies leads to very short isolated pulse. b) An initially short pulse gets stretched in time after passing through a slab of material. This is a result of the dispersion of the refractive index with frequency that is found in any real material. c) Pulse broadening experienced by an initially short Gaussian pulse with 800 nm center wavelength after propagating through fused quartz. The curves indicate the pulse broadening factor as a function of the incident pulse duration for three different thicknesses of fused quartz. An initially 10 fs long pulse will thus be 1 ps long after only 10 cm of fused quartz, whereas a 1 ps pulse will not have noticeably broadened after the same amount of material.

A more detailed analysis of how dispersion affects ultrashort pulses shows that the curvature – i.e., the second derivative – of the refractive index as a function of frequency is the lowest order that broadens the pulse. If this curvature is positive for a material at a given frequency, this material is said to exhibit positive dispersion and negative dispersion for negative curvature. In a positive dispersion material, lower frequencies propagate faster than higher frequencies. As a result, a pulse where all superimposed frequency components perfectly line up at the input to a material will display a frequency ramp from low to high frequencies at the output (Fig. 1b). Based on the sound a corresponding acoustic wave would make, this variation of the instantaneous frequency across the pulse is referred to as chirp. In the visible to near-infrared spectral region, where most ultrashort pulse lasers operate, essentially all optical materials exhibit positive dispersion and thus lead to a chirp from low to high frequencies (called a positive chirp).

The compensation of dispersive pulse broadening or chirp is one of the main considerations when working with ultrashort optical pulses. After all, one usually aims for having the shortest pulses available at the position where the pulse interacts in an experiment or application. Since for the most common laser frequencies all materials impose the same sign of dispersion, compensation can typically only be achieved with artificial structures, which will be briefly discussed below.

As stated in the introduction, a short pulse can reach considerable intensities with moderate amounts of energy. As a consequence, the refractive index of a material will not only depend on frequency, but may also depend on intensity. The lowest order intensity-dependence of the refractive index that can be found in all materials is mediated by the optical Kerr effect. The resulting refractive index can be written as $n = n_0 + n_2 I$, with n_0 representing the normal, linear optical refractive index found at low intensity, n_2 the nonlinear refractive index coefficient, which is a material property, and I the light intensity, which can be a function of time and spatial coordinates. From this simple relation follows that an ultrashort optical pulse, that by definition has an intensity that rapidly changes with time, will induce a rapid refractive index modulation if it has sufficient peak intensity. This rapid modulation acts back on the pulse itself (therefore referred to as self-phase modulation) and results in the generation of new optical frequency components. In conjunction with dispersion, self-phase modulation can lead to unwanted pulse distortions.

Considering a laser beam with a typically Gaussian transverse intensity profile, the optical Kerr effect will impose a Gaussian refractive index profile in the spatial domain through the above relation. Similar to the self-phase modulation, this refractive index profile will act back on the beam itself. A Gaussian refractive index profile (or, in general, any approximately parabolic profile) will have a focusing effect on the beam. This self-focusing leads to a further concentration of the light, which in turn leads to an increased intensity and thus stronger self-focusing [5]. It is clear that such a positive feedback loop can lead to damage in optical components if the propagation length through the material is sufficiently long. The higher the initial intensity, the shorter the propagation distance after which damage through self-focusing can occur. Even if the intensity for damage in one component is not reached, the self-focusing action can cause the beam to shrink further downstream in an optical setup and cause the beam to exceed the damage threshold at a remote piece of optics (Fig. 2).

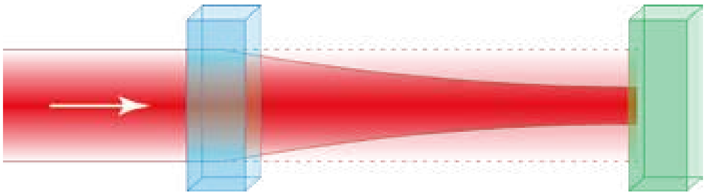


Figure 2: Self-focusing of a laser beam through the optical Kerr effect. While a low-intensity beam passes the blue material without changing its divergence (indicated by dashed lines), a high-intensity beam experiences self-focusing due to the intensity-dependent refractive index. Depending on the propagation length in the material and the intensity of the beam, laser-induced damage may occur within the focusing material directly (blue slab) or further down the optical path on a remote optical surface (here, the green slab).

The nonlinear effects described above with their resulting beam distortions and material damage were for a long time hindering the development of intense sources of ultrashort optical pulses. This roadblock could only be overcome with the invention of CPA.

3. Chirped-pulse amplification

The basic idea of CPA is to prevent the unwanted nonlinear effects and ultimately damage of optical components by stretching the pulse considerably before its amplification. In a typical femtosecond amplifier system, the pulses would be stretched to many nanoseconds prior to amplification. Such a stretching factor of about 10^5 to 10^6 leads to a corresponding reduction in peak power and intensity at a given pulse energy. As a pulse stretcher, we can use propagation in a dispersive medium as described above. Indeed, propagation through a glass fiber was used in the first demonstration of CPA by Strickland and Mourou [4]. However, in the application or experiment, one would still like to have a short pulse with the associated high peak power and intensity. After amplification, the pulses are therefore recompressed by imposing dispersion with the opposite sign to that of the stretcher. How can such a pulse compressor be implemented given that at the typical visible to near-infrared operation wavelengths of the most common amplifier systems materials only exhibit positive dispersion?

Effective negative dispersion can be obtained even in this wavelength region with artificial structures exploiting frequency-dependent diffraction, refraction or interference. The most common pulse compressor type for high-peak-power amplifiers is depicted in Fig. 3a) [6]. It exploits the angular dispersion of the polychromatic ultrashort pulse upon diffraction off a grating. A second identical grating compensates the angular dispersion of the first one, leading to all frequencies forming parallel beams at its output. A second pass in opposite direction through this arrangement assures that all frequency components are collinear again. A detailed geometrical analysis of this setup shows, that low frequencies (indicated in red in Fig. 3a) always have to travel longer pathways than the higher frequency components of the pulse (blue). Therefore, at the output of the compressor, the high frequencies are advanced with respect to the low frequencies, which can compensate a positive chirp that was previously imposed by a pulse stretcher. The amount of negative dispersion added by the compressor can be tuned by varying the distance between the two gratings.

The solution used in the original paper by Strickland and Mourou with a pulse stretcher using material dispersion and a grating compressor is not ideal. It is found that the compressor can compensate the chirp imposed by the stretcher only to lowest order. Uncompensated higher dispersion orders lead to unwanted pulse distortions, effectively reducing the maximum achievable peak intensities by not being able to concentrate all the available pulse energy into a single light burst of minimum duration. Martinez et al. [7] demonstrated that by adding two identical lenses with focal length f between the gratings of the pulse compressor, the resulting arrangement produces positive dispersion if the gratings are placed at a distance $L < f$ from their respective closest lens (Fig. 3b). Even better, the dispersion, including higher orders, will correspond to that of a grating compressor with a grating separation of $L - f$. This means, the addition of the lenses effectively produces a grating compressor with a negative grating separation. Since the magnitude of all dispersion orders is proportional to the grating separation, their sign is now flipped compared to a compressor with the same, but positive distance between the gratings. As a result, a grating compressor can fully compensate the dispersion imposed by a grating compressor to all orders. In practice, since also the amplifier material and other components along the beam path will add positive dispersion to the pulse, dispersion compensation will never be absolutely perfect across all orders. The system is then optimized for minimal dispersion in the dominating lowest orders.

In a standard laboratory sized amplifier system, the ultrashort pulses at the beginning of the CPA chain have a duration of tens of femtoseconds with nJ pulse energy. These pulses are stretched to nanoseconds duration and then amplified to many mJ energy. After recompression, the pulses are roughly back to their initial duration, but now with tens of GW peak power. In larger systems, final energies exceed several J and the peak power can reach up to 10 PW. It becomes clear that with such high peak powers and the associated intensities, care has to be taken with respect to the materials and components along the beam path following the compressor. As a result, for the highest-peak-power systems, the compressor and all of the subsequent beam path are placed in vacuum as otherwise even air would induce substantial self-focusing.

While the idea behind CPA appears to be simple, it represented a major breakthrough for intense laser science and associated fields. It enabled a broad range of applications and research directions that would otherwise be out of reach. It is for this tremendous impact that Donna Strickland and Gérard Mourou have been awarded with the 2018 Nobel Prize in Physics.

4. Applications of chirped-pulse amplification

CPA has enabled the construction of comparably compact high-peak-power and high-intensity laser systems that achieve their parameters by compressing moderate amounts of energy into very short – typically femtosecond – pulses. A relatively standard laboratory-sized system can now produce pulses with a peak power exceeding a TW.

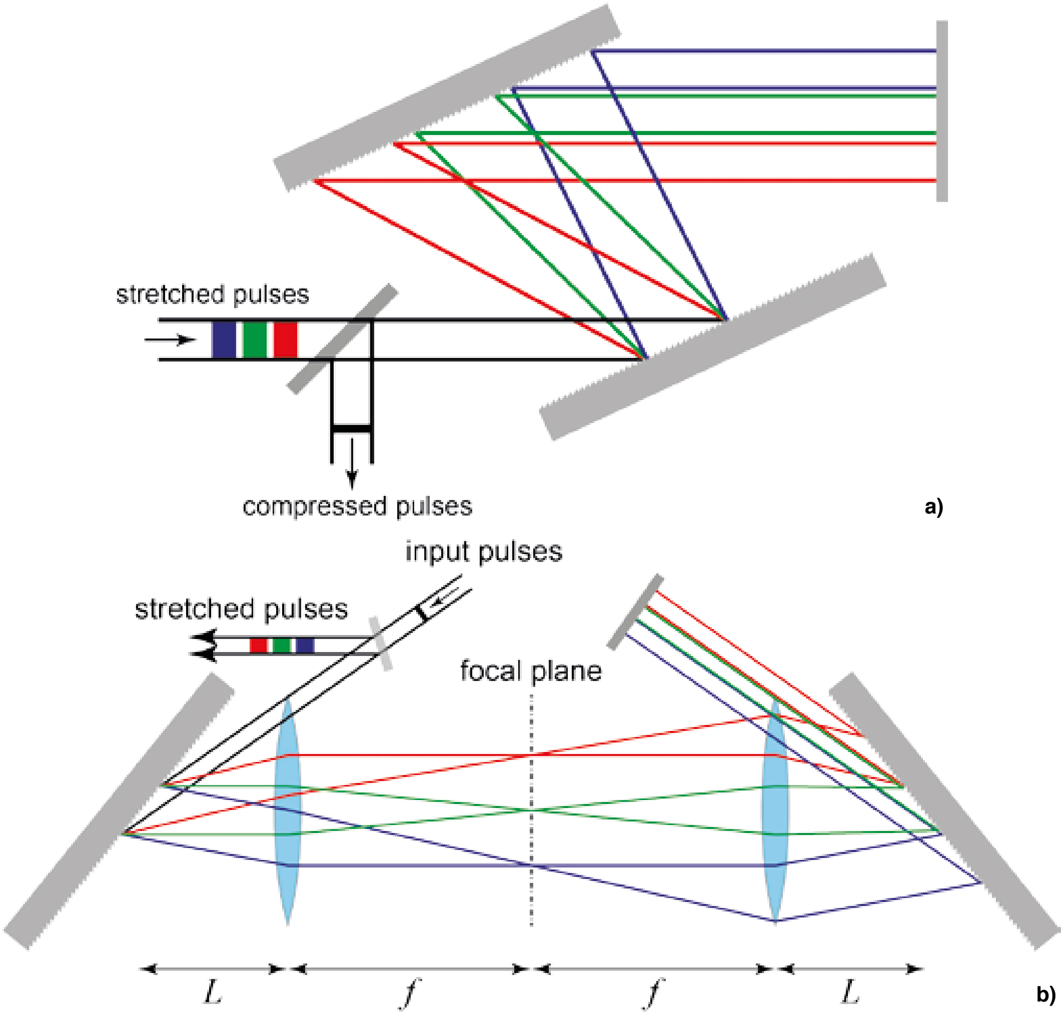
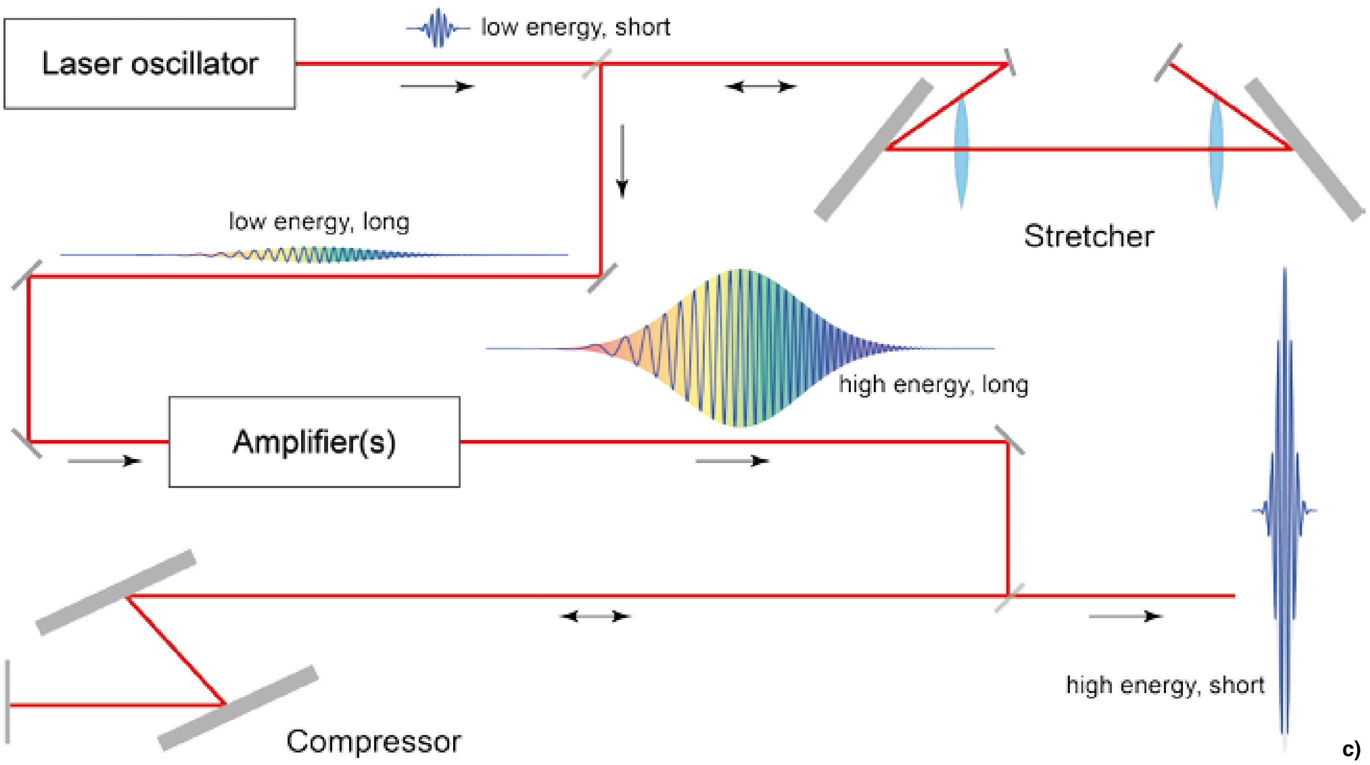


Figure 3: Chirped-pulse amplification using a grating-based stretcher and compressor. a) An arrangement of two diffraction gratings in double-pass imposes negative dispersion on an ultrashort optical pulse. Thereby it can compensate for a positive chirp of the initial pulse and recompress the wavepacket to short duration. b) By appropriately adding two identical lenses between the two gratings, the sign of the imposed dispersion can be flipped. Such an arrangement is typically used to stretch the pulse before amplification. c) A complete CPA system consists of a laser oscillator producing short, but low-energy pulses. After a stretcher, these pulses are amplified to substantial energies. To regain the short pulse duration and at the same time achieve a high peak power, the pulses are finally sent through a pulse compressor.
(Illustrations inspired by https://en.wikipedia.org/wiki/Chirped_pulse_amplification)



Larger laser systems, such as those being in their final phase of construction for the European Extreme-Light Infrastructure (ELI) will even reach 10 PW [8]. What compact means becomes apparent when comparing CPA systems with the highest-energy lasers that are still based on pre-CPA technology [9, 10]. The National Ignition Facility (NIF) at Lawrence-Livermore National Laboratory, for example, fills a large building (see [9] for a visualization) and fires approximately one laser shot per day. While the 10 PW laser of ELI Beamlines near Prague still fills a large room [11], it produces 200 times higher peak power and fires once every minute. It reaches this peak power and pulse repetition rate by compressing three orders of magnitude less energy into a pulse of only 130 fs instead of the several-nanosecond bursts used at NIF. In the following, a few examples of scientific applications made possible by CPA lasers are given.

At laser peak intensities on the order of 10^{14} W/cm^2, the electric field in the optical pulse becomes comparable to the inner-atomic binding forces and field-ionization may occur. Given the oscillating nature of the optical field, liberated electrons are further accelerated and may eventually return to their parent ion. Upon recollision with the parent ion, the electron may recombine with the ion and release excess energy in the form of a high-energy photon. With initial laser pulses in the near-infrared, the generated photons reach into the extreme ultraviolet spectral range. This laser-like, coherent extreme ultraviolet radiation is intrinsically concentrated into sub-femtosecond bursts [12, 13]. The described process lays the foundation of attosecond science. While the motion of atomic nuclei is frozen on sub-femtosecond scales, electrons are light enough to exhibit attosecond dynamics. Attosecond science has extensively studied the dynamics of ionization processes in atoms, molecules and from solids [14-17]. Recently, the field expanded towards studying electronic processes in condensed matter systems [see the authors article on p. 11 in this issue]. Attosecond science yields new insights on fundamental physical processes on atomic time and length scales that were previously inaccessible. Processes that were treated as instantaneous in the past have to be reconsidered. This entire research direction became possible only thanks to CPA, that enabled tabletop laser systems with tens of femtosecond pulses and the required focused intensities.

At the intensities presently used in attosecond science, the electrons still move non-relativistically in the focused laser beam. State-of-the-art laser systems, however, reach to almost ten orders of magnitude higher peak-intensity, which gives access to much more extreme regimes of laser-matter interaction. Systems with TW-level peak power are used for laser-driven particle acceleration. Given the extremely high electric-field gradients that can be reached with lasers, electrons can be accelerated to energies of many GeV over centimeter distances. At laser intensities on the order of 10^{18} W/cm^2 the oscillation energy of an electron in the electric field of a laser pulse becomes comparable with its rest mass, which defines the onset of relativistic interactions of free electrons with light. PW-class lasers open up access to the ultra-relativistic regime with intensities up to approximately 10^{23} W/cm^2. Such lasers enable research in extreme regimes of laser-matter interaction that are relevant for laboratory-based studies of astrophysical processes or for driving nuclear reactions. A holy grail of high-intensity laser physics is to reach the energy densities required for particle production from vacuum (i.e., separating a virtual positron-electron pair into real particles).

While these intense lasers allow studying fundamental physics directly, they can also be used to drive a wide range of secondary sources beyond the particle acceleration already mentioned above. Such lasers produce extreme ultraviolet radiation through high-harmonic generation, x-rays by heating a plasma or driving electrons through an undulator, and even intense gamma-rays beyond 10 MeV photon energy using mechanisms such as Compton back scattering. These sources are of immediate interest for a multitude of applications even if ultrafast time resolution is not needed.

5. Conclusion

As the examples above illustrate, CPA has allowed ultrafast lasers to reach into domains of physics well beyond ultrafast science itself. In addition to basic research, CPA had an impact for medical and industrial applications. High-power CPA fiber laser systems are now in use for precision micromachining in industry, but also for eye surgery in medicine. At the same time, high-intensity lasers offer the perspective for a wealth of future medical applications through their ability to produce beams of particles and high-energy photons as well as medically relevant radionuclides through laser-driven nuclear reactions.

The beauty of CPA lies in its simplicity and broad applicability. It has enabled the scaling of peak power and intensity by many orders of magnitude, which has given rise to entire new fields of research. The CPA method first demonstrated by Strickland and Mourou had a tremendous impact on science and beyond by virtually eliminating the significant technological constraints of the past. It is this impact that has been recognized by awarding one half of the 2018 Nobel Prize in Physics to Donna Strickland and Gérard Mourou. Even more than 30 years after it has been reported for the first time, CPA technology keeps pushing laser parameters towards new extremes, yielding access to unexplored regimes of light-matter interaction.

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Laser tweezers for the nanoworld *

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Nature is made of discrete building blocks - atoms and molecules in the physical world, large biomolecules and cells in living systems. To precisely manipulate these building blocks, to study their function one at a time and to assemble them into larger systems has been a long-standing dream of science. With the invention of the optical tweezer and related laser trapping and manipulation tools, this dream has come true. One half of the Nobel prize in physics 2018 goes to Arthur Ashkin (Fig. 1), who pioneered these techniques since the early 1970s.

The fact that light can exert forces on matter had been known for a long time, postulated by Kepler to explain comet tails and finally observed in the lab in delicate precision experiments in the early 1900s. However, the optical forces were much too weak to be of practical use. This changed with the invention of the laser in 1960, which provided an intense and coherent source of light that can be tightly focused and precisely aligned. Soon after the first lasers became available, researchers began to study optical forces as a tool to manipulate small particles.

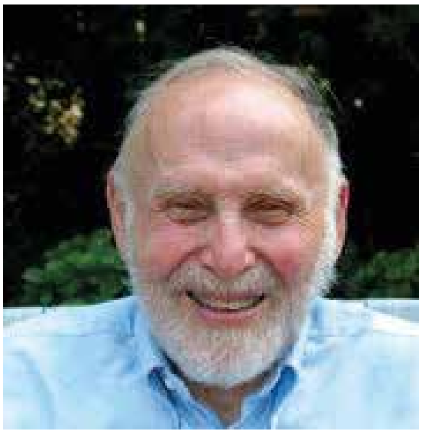

Figure 1: Arthur Ashkin invented the optical tweezer, which revolutionized atomic physics and the life sciences. Image: Aline Ashkin

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* a shorter version of this article appeared in the *SPG Mitteilungen* Nr. 56, October 2018

Arthur Ashkin at Bell Laboratories in New Jersey reported a first success in 1970, demonstrating radiation pressure forces on small particles in water and air [1], followed soon by the demonstration of optical levitation with a gravito-optical trap [2]. In 1986, Ashkin and his co-workers reported the first all-optical single-beam trap [3], which soon became known as "optical tweezers". It allows to confine small dielectric objects to the intensity maximum of a tightly focused laser beam (Fig. 2). By steering the laser beam around, the objects can be precisely positioned and manipulated.

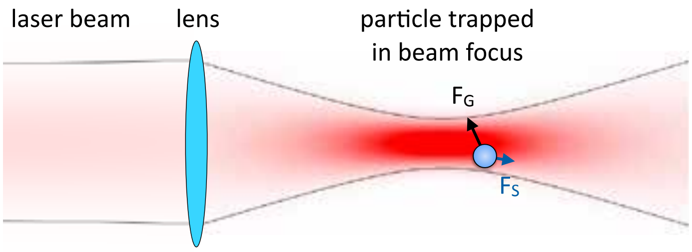

Figure 2: Optical tweezers: a tightly focused laser beam traps a small dielectric particle near the beam focus. The trapping relies on the gradient force F_G, which pulls the particle towards the maximum of the light intensity an thus provides both transverse and longitudinal confinement. For particles of suitable size in a tight focus, F_G is stronger than the scattering force F_S, which always pushes the particle in the direction of beam propagation.

Two different types of forces can be distinguished in optical trapping of dielectric particles: the first is the "scattering force" F_S, which arises from the laser photons that impinge on the particle and are scattered out of the laser beam. Since photons carry momentum, each photon imparts a momentum kick to the particle. The momentum kicks from the incoming photons are always directed along the laser beam propagation direction and add up, while the scattered photons fly away in random directions and their momentum kicks average to zero. The net result is a force F_S proportional to the light intensity and directed along the beam's propagation direction (Fig. 2). The scattering force can be used to manipulate particles, but it alone does not allow for stable trapping with a single beam of light because it would continue to accelerate the particle along the laser beam.

Optical tweezers rely on the second type of force experienced by the particle in the laser focus: this is the so-called "gradient force" F_G, which is proportional to the intensity gradient of the light and points along this gradient (Fig. 2). Unlike the scattering force, the gradient force can thus provide both transverse and longitudinal confinement of the particle in a focused laser beam. To understand the gradient force, two different pictures are helpful, depending on the size of the dielectric particle. A particle that is larger than the wavelength of light can be thought of as a small lens that refracts the laser light. Momentum conservation requires that each photon changing its propagation direction imparts momentum to this tiny lens, resulting in a force on it. A ray optics analysis shows that this force confines the particle to the laser beam focus if the particle's refractive index is larger than that of the surrounding medium [3]. For a particle that is smaller than the wavelength, an explanation based on the dielectric polarizability of the particle is more accurate: the electric field of the laser beam polarizes the particle and the resulting electric dipole experiences a force in the very same laser field, pulling it towards the intensity maximum for positive polarizability. For a particle of suitable size in a tightly focused laser beam the gradient force is stronger than the scattering force. As a result, the particle is trapped near the intensity maximum of the beam focus, where the two forces compensate each other.

A remarkable feature of the optical trapping techniques developed by Arthur Ashkin and his collaborators is that they can be applied to a wide variety of different objects, ranging from atoms and molecules to dielectric nanoparticles, large biomolecules such as DNA, and even living cells and small microorganisms. As a result, the invention of optical trapping kick-started several fields of research in different domains of science.

In atomic physics, laser traps and related laser cooling schemes were soon used to trap clouds of atoms and to cool them to microkelvin temperatures. Experiments with such ultracold atoms in laser traps made it possible to study quantum physics with unprecedented control and precision [4]. This led, among other things, to the observation of novel states of matter, such as Bose-Einstein condensation, and to the development of the most accurate atomic clocks and other atomic precision measurement devices. The optical trapping techniques for ultracold atoms have been continuously refined, and it is now possible to use computer-controlled arrays of optical tweezers to arrange individual atoms in nearly defect-free three-dimensional patterns of arbitrary shape [5]. The figure on the front page shows example patterns which were recorded by imaging the fluorescence of the atoms (Image: Browaeys group, Institut d'Optique, Palaiseau, adapted from [5]). These techniques currently play an important role in the development of quantum technologies.

Optical tweezers have also enabled an entirely new set of precision experiments in the life sciences, which has revolutionized the field of single-molecule biophysics. Already in 1987, Arthur Ashkin used optical tweezers to trap living bacteria without harming them [6]. For the first time it became possible to perform controlled mechanical manipulations of individual living cells, benefitting from the fact that the optical forces can be applied to these objects in their natural environment under ambient conditions. Ashkin noticed that even structures within the cell could be moved and manipulated by the optical force. A major breakthrough came in the 1990s, when scientists realized that optical tweezers can reveal the mechanical properties of individual motor proteins, which are macromolecules that move and transport cargos along

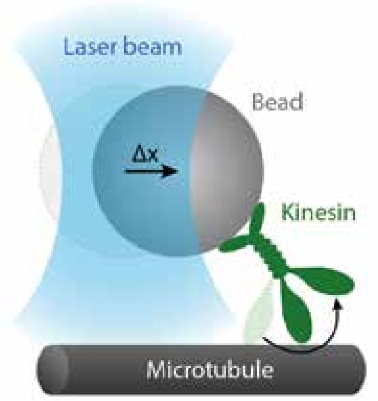

Figure 3: Studying the movement of molecular motors using optical tweezers. The molecular motor (here kinesin) is directly attached to a polystyrene bead that is trapped using optical tweezers. The tracks of this motor (microtubule) are attached to the surface of the sample chamber. Movement of the motor can be measured through the movement of the trapped bead.

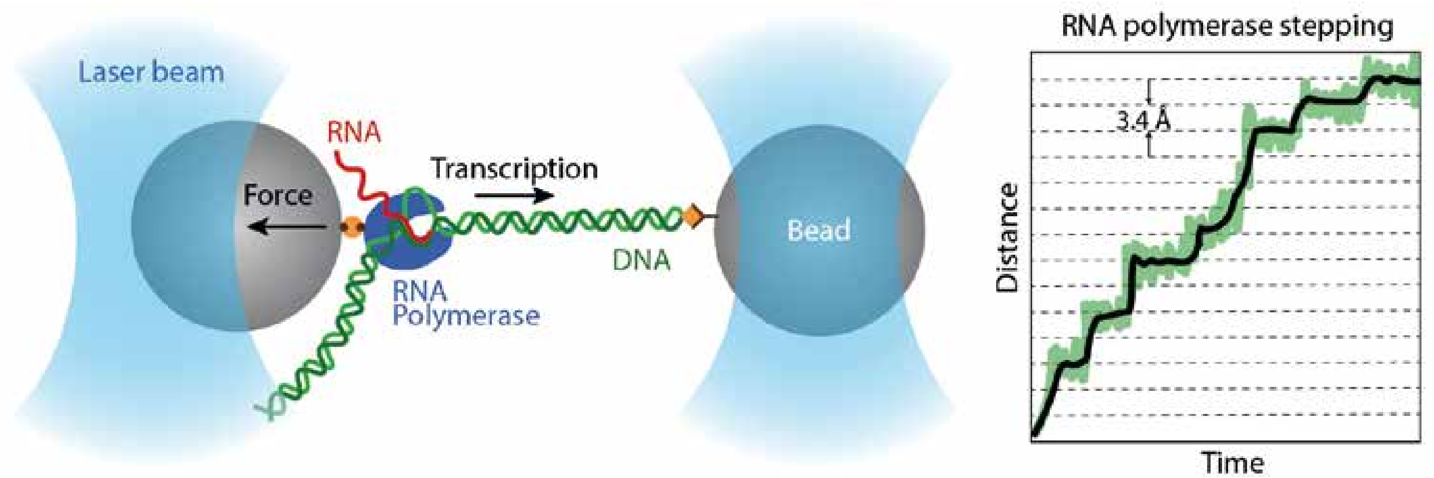

Figure 4: Tracking RNA polymerase transcription elongation using optical tweezers. Left: Schematic illustrating transcription elongation experiments using optical tweezers. Two beads are held in two optical traps in a dumbbell geometry. The RNA polymerase is attached to one of the beads and the end of the DNA to the other bead. When the polymerase is transcribing DNA into RNA, it moves along the DNA against the force exerted by the optical trap. Thus, the enzymatic reaction is slowed by the external force. The amount of force applied can be inferred from the displacement of the beads from the center of the optical traps. To calculate the movement of the polymerase, both the stiffness of the optical trap as well as the force extension behavior of the DNA have to be accounted for. Right: Exemplary high-resolution optical tweezers data of RNA polymerase transcription elongation showing individual single base pair steps.

the skeleton of a cell. When an individual motor protein is attached to a dielectric bead held in an optical trap, the motor's movement can be measured through the forces it exerts on the bead (Fig 3). In this way, the 8 nm steps of the motor protein kinesin along its track could be measured for the first time [7]. Since these first studies, the resolution of optical tweezers has dramatically improved such that it is even possible to observe the 3.4 Å steps that the RNA polymerase takes as it reads the genetic code (Fig. 4).

About 50 years after it started, optical trapping of particles continues to be a dynamic and exciting field of research. Most recently, techniques for optical levitation have been used in the new field of optomechanics to trap dielectric nanospheres in vacuum (Fig. 5) and cool them close to the quantum mechanical ground state [8,9]. Such experiments could lead to novel tests of quantum physics with massive, mesoscopic objects and find applications in precision force sensors operating at the nanometer scale. In the life sciences, optical tweezers have become a widely used tool for interrogating and manipulating individual biomolecules and subcellular structures. Recent advances include the application of optical holography to simultaneously use thousands of optical traps in high-throughput experiments and the integration of optical tweezers with super-resolution microscopy to simultaneously and correlatively visualize and manipulate molecular interactions with sub-piconewton and sub-nanometer resolution. This shows that the work of Arthur Ashkin, which has been honored with the Nobel Prize in physics 2018, continues to have significant impact even today.

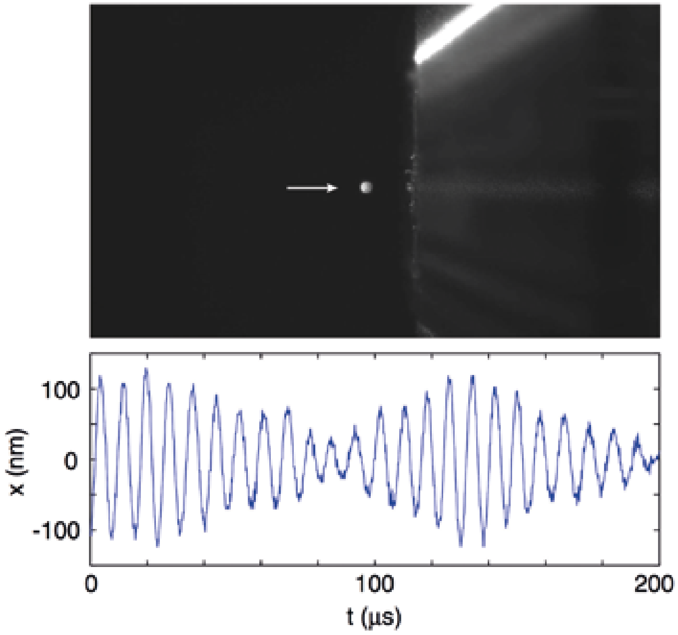

Figure 5: Top: Photograph of light scattered from a silica nanoparticle (arrow) that is trapped in the focus of a laser beam. On the right, the outline of the focusing objective can be seen. Bottom: time trace of the particle's motion transverse to the optical axis, which is recorded by measuring the phase of the scattered light. Image: Novotny group, ETH Zürich, adapted from [8].

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Physicists in Industry (8)

In our series *Physicists in Industry* we regularly inform about the activities of, well, physicists in industry, but also what they recommend to students when those are looking for a job after completing their studies. In addition to research activities in large-scale industries like IBM, many graduates join or even set up start-up companies based on their innovative ideas. The lack of business experience can be compensated e.g. by special mentor programs of *Innosuisse*, the Swiss Innovation Agency. But physicists should also move more and more to SME that are already established on the market but need innovation, especially when considering the increasing complexity of arising technologies (see *SPG Mitteilungen* Nr. 56 on p. 44). All these points were addressed at our last year's annual meeting at EPFL in the special session *Physics beyond University*, organised by the SPS section "Physics in Industry", which attracted many listeners (dito, page 11).

One of the speakers was Nikola Pascher, who gave a very enthusiastic talk for students about her exciting work at Nanosurf. *Andreas Fuhrer*, SPS section head, interviewed her after the meeting.

"Surfing the Nanoscale with Dr. Nikola Pascher"

Nikola, you are head of R&D at Nanosurf, a company developing scanning probe instruments ... (see box).

Nanosurf has already visited Mars. Where do YOU want to go with Nanosurf technology?
Nanosurf is currently in a really interesting transition phase. The company started as a supplier of instrumentation for teaching and managed to establish a leading position in this very specialized market. Growth is limited in that niche, so expansion into different areas becomes necessary. Currently we are increasing the performance of our instruments to access a high-end market. This is extremely exciting. My personal goal is to make this happen together with our R&D team.

Nanotechnology emerged from scientific research of physicists investigating structures at the length scale of a few atoms.
From your perspective, building tools for nanoscale characterization, are your main clients still in physics or has nanotechnology become even more important for other fields?
Nanotechnology is very broad. It covers material science and physics, but it is also getting bigger and bigger in life sciences. These research fields are extremely interesting and relevant for our daily life. New areas are emerging fast. For instrumentation, this is important as these fields of research impose entirely new demands on scientific instruments. While samples in physics are usually made of metals, semiconductors, etc., samples in life sciences consist of biological tissue. They are often alive. We have to be creative in how we measure such samples without seriously damaging them. We put a lot of thought into how to create the greatest benefit for the researcher with our instruments.

Innovations are central to your business. Is it more the push from new nanotech research results or the pull from different markets that drives the development of scanning probe technology tools?
It is both. I would say for us it is rather the push from the nanotech researchers. Our customers are mostly scientists at universities who want our instruments to contribute to hot topics in research. Our instruments need to empower them to do this.

What is your vision/wish for the future in your role as head of R&D at Nanosurf?
I really love to work with instruments that have a great performance, solve my problems, are easy to handle and beautiful to look at. Sometimes the instruments even inspire me to discover things I have never thought about before. My vision is that we develop great and inspiring high-end products with breath-taking performance to make amazing science possible.

What are the key hurdles when turning a working "lab demonstration" into a real product?
When I started at Nanosurf, I was surprised of how perfect an instrument has to be in order to be accepted on the market. When setting up an experiment in a university lab, it

About Nanosurf:
Nanosurf, founded in 1997, is a Swiss-based provider of scanning probe microscopes. Our products are developed and produced in our headquarters in Liestal by our dedicated team of experienced engineers and physicists, and sold worldwide. Our product range includes the most compact AFM and STM instruments on the market, state-of-the-art research in atomic force microscope systems, and customized and comprehensive next-level solutions. Our customers in research, industry and teaching value the innovative approach, modularity, and ease of use of our solutions.

About Nikola:
Nikola's career path started at the University of Augsburg in Germany, where she studied Physics. After graduation, she moved to ETH Zürich for her PhD and a subsequent postdoc project at IBM Research. Her work triggered a passion for scanning probe microscopy and precise scientific instrumentation. After a period of working as a senior research scientist at Nanosurf, she is now heading the Research and Development department of this company.

is usually a single person or a very small group of people who operate it. Under these circumstances the main goal is to obtain scientific results quickly. To make the instrument easy and efficient to operate is usually secondary. When a prototype is supposed to become a product, everything from mechanics and electronics to software has to be perfect, polished and working together nicely. The time it takes to fine-tune all processes tends to be underestimated.

How important is the local research landscape in Switzerland for a technology company like Nanosurf? (location (Liestal), employees, education, funding, technology providers, ...)

Nanosurf would never be where it is now if it was not for our great university partnerships. All R&D of Nanosurf is located in Liestal. From there it is very easy to maintain excellent connections to the University of Basel, ETH Zürich and EPFL in Lausanne. Our collaborators are usually active in scanning probe microscopy or in the development of instrumentation. As a small company, it is almost impossible to maintain lab-space and find time to do great experiments that lead to publishable results. First experiments with our instruments are usually carried out together with our collaborators in a university lab. On top of that, with their scientific publications these collaborators help us advertise our products and their capabilities. We collaborate with several groups that are active in development of instrumentation or nanotechnology research. We profit greatly from their ideas and innovations. Switzerland has very useful funding schemes for companies close to university research. Nanosurf always has a number of running Innosuisse projects and is grateful for this kind of support.

Do you still use physics every day?

Absolutely. Compared to my work at the university my use of physics is now a lot broader. When doing a PhD or a postdoc the goal is usually to focus on a specific topic or problem. In my position as Head of R&D it is necessary to understand all the topics covered by nanotechnology, ranging from material science to biology. The trend in atomic force microscopy goes towards instruments operating close to their physical limits. To do this, a thorough understanding of the underlying physical principles is necessary: How to build up the mechanics of the instrument for optimal performance? What can be accomplished with optics? How can things be miniaturized and optimized for reliability and cost? What is possible with electronics and software? I find this playground, that connects physics to different disciplines of science and engineering extremely inspiring and I learn new things every day.

What did you dream to become as a kid? Did that dream come true? Was the path you took a direct line or more a bumpy road?

I think the path never was a direct line, but all the experiences I made were necessary for me to develop to who I am today. Even when I was a kid, I realized that developing a dream and living it is not an easy task. The world around us changes rapidly and our life is a constant process of learning. In this process the perspective on the future is bound to change continuously. So, I think even though it is important to be focused and to try to make a personal dream come true, it is also important to adapt the dream when the circumstances and underlying assumptions change. Not looking left and right from a precise goal might lead to a lot of missed opportunities.

For myself I would say, that I never had a dream like “I want to become the head of R&D at a nanotechnology company” but rather had ideas of what I would like to be on a different level. I knew for sure that my goal in life would be to do things I find inspiring, to enjoy what I am doing and to meet and work with interesting people. To do cutting-edge science and engineering fulfills all of these criteria. So, for the present I would say that my dream has come true. As for the future, I am curious of where it will take me.

You are one of the rare examples of a woman in a leading technical position. What, in your opinion, could be done to improve the gender balance?

This is a difficult topic. I think that the routes of this gender imbalance are buried deep in our thinking, our education and our society. Men and women often behave differently in given situations. These ways of behavior might trigger different impressions with decision makers. I don’t think this is usually a process which comes from bad intentions, but rather from an unconscious bias.

Like with many challenges in our society, I think that education is the key. While studying physics or engineering learning is usually focused completely on the technical part. Yet the development of good social and behavioral skills might benefit from training also. These topics would be immensely helpful in everyday professional life.

We should raise an awareness for unconscious bias in our society and start to reduce it. Schools and universities could offer courses to train both men and women on these behavioral topics. Apart from learning we also need to change our procedures and processes to remove gender bias, like e.g. the selection process for important positions.

Were there points in your life at which you believe the path you chose (that was decided for you) would have been different if you had been a man?

When I try to think of the points in my life when I made serious decisions, I have the impression that there were plenty of aspects that were more important than gender. I decided to study physics, because I loved this science and felt my talent lay in this area. I decided to do my PhD at ETH because I liked the topic, the people and the place. And so on. Of course, sometimes, I, as a woman in physics, was treated in a special way (“Good morning gentlemen, good morning Ms. Pascher”), and it was not always easy to laugh about this. Yet I don’t think that this has ever influenced my decisions.

Any recommendations to female students? What should they do to find an exciting job in physics?

Don’t let other people tell you what your role is and always question your - and other people’s assumptions. Enjoy what you are doing and work with a lot of enthusiasm. If you don’t manage to be enthusiastic for what you are doing, it might be time for a change. Be open-minded and look for new challenges.

Physics and Society

Let’s Talk About Open Science

Martin Vetterli, President of the EPFL, presidence@epfl.ch,
Luc Henry, Scientific Advisor at the Presidency, EPFL, luc.henry@epfl.ch

This article is the written version of the public lecture given by Martin Vetterli at the SPS Annual Meeting 2018 in Lausanne.

In 1989, English telecommunication engineer and CERN fellow Tim Berners Lee wrote a 'vague, but exciting' proposal to build a hypertext project called "WorldWideWeb" [1]. The rest is history. As of June 2018, an estimated 55% of the 7.5 billion people living on this planet have access to the Internet via the Web. It has become the backbone of the Information Age we all live in, the cornerstone of our modern digital culture and of its communication revolution.

What is well known is that a CERN scientist invented the Web. What is lesser known is that it was initially invented *for* scientists. More precisely, the goal was “*to allow high-energy physicists to share data, news, and documentation*” as Tim Berners Lee explained on an internet forum in August 1991. Anticipating the enormous potential of the Web technology, he insisted that it should not be restricted to his discipline. “*The Project started with the philosophy that much academic information should be freely available to anyone. It aims to allow information sharing within internationally dispersed teams*”, he wrote in another memo addressed to the early adopters and supporters of the Web.

Open Science and Digitalization

Open science is based on the assumption that the discovery process should be carefully described and ultimately shared so that everyone can critically assess the results and build on them or make new discoveries [2]. It can be debated whether the Web is the cause or the consequence of the open science movement we witness today. What is clear is that it was conceived as a tool to support global collaboration in science. It has dramatically changed, and is still continuously changing, the way we discover, produce and share knowledge.

Beyond the Web, it is digitalisation in general that has triggered a transformation in research and education. The academic institution is in a transition, much like the rest of society. Computers are used in virtually every step of the research process, from generating a hypothesis to disseminating results. Scientists use search engines to find relevant documents in the ever-expanding volume of literature, store their observations, measurements and models in digital files on servers, craft algorithms to sort, analyse and visualise the data, and use the web again to share all of this with colleagues across the globe. Some compare the impact of computers and networks to what happened during the first scientific revolution when the printing press was invented. One can wonder: is digitalisation triggering another scientific revolution?

What is surprising is that, although our means of communication have evolved so dramatically, the format used for the dissemination of scientific knowledge within the academic community has remained relatively unchanged. In 1665, German theologian and natural philosopher Henry Oldenburg joined forces with Robert Boyle, considered the first modern chemist and one of the pioneers of the experimental scientific method, to launch the *Philosophical Transactions* of the Royal Society. It was the first journal in the world exclusively devoted to science and the first to adopt peer review. The publication process was put in place to fulfill five main roles: documentation (detailed description of the experiment and the results), registration (list of authors and date stamp), certification (through peer review), dissemination (via subscriptions) and archiving (in libraries). With the advent of scientific journals, the reputation economy of academic scholarship was born.

Some voices say that the format adopted by the *Philosophical Transactions* in the 17th century is out-dated today. The complexity of contemporary research methodologies and results cannot simply be described in words, tables and static figures anymore. The problem started to appear over two decades ago with the advent of computers in research, leading to the apparent expansion of the scientific method [3]. Inspired by Stanford professor of geophysics Jon F. Claerbout [4], James Buckheit and David L. Donoho expressed their concerns in the following statement: “*An article about computational result is advertising, not scholarship. The actual scholarship is the full software environment, code and data, that produced the result.*” [5] [6] The rationale is that, in order for others to verify and build upon their work, researchers have to share more than just a wordily description of their methods. The documentation required to guarantee an acceptable level of reproducibility in chemistry and other natural sciences was not sufficient in an era when scientists increasingly used computer models and large data sets to make discoveries and prove hypotheses. While errors are a crucial component of the scientific enterprise, only transparency allows others to correct them.

After over 350 years of going virtually unchanged, it may be time for the ‘paper’ format to be rethought. Its limitations, exacerbated by the commodification of knowledge that big publishers have put in place through paywalls as they consolidated their catalogue of journals, start to transpire in every field of research [7]. The foundation of open access were laid over two decades ago, but today, open science supporters promote public access to the data, the computer code, algorithms, and other digital products that support the results described in research articles. They seek to solve the problem of under-reporting or misinterpretation of results that led to a perceived reproducibility crisis [8]. Or they want to tackle insufficient skills and infrastructures that would allow coping with the ever-increasing importance of computers and digital data in research (see for example the teaching programs by the community initiative *The Carpentries* [9]). As a consequence, new practices emerge in the research community, together with new expectations from journals and funding agencies, but also from the public.

By going back to Tim Berners Lee's original vision, open science initiatives are bringing back digital innovation to academia and changing the way researchers make and share discoveries. They use the Web to its full potential and explore new strategies allowing 21st century science to thrive.

The Promises (and Challenges) of Open Science

A number of influential scientific institutions have released reports that identify the potential impact of open science practices. As early as 2012, the Royal Society has laid out the vision, and the necessary steps to enable its realisation [10]. More recently, the American National Academies of Sciences, Engineering and Medicine systematically mapped the benefits and motivations, as well as the barriers and limitations of an implementation of open science principles [11]. The authors of the report put the researcher at the centre of the concept of open science by design, expecting them to both contribute and take advantage of the open science practices. Their assumption is that research conducted openly and transparently leads to better science. Indeed, open science is a vow to invest into best practice that will eventually lead to the following outcomes:

Visibility = larger impact
Scrutiny = better quality
Reuse = higher efficacy
Public access = fair opportunity

Physics has been at the forefront of open science in many ways. One salient example is the widespread adoption of digital preprints as soon as Paul Ginsberg launched the online repository [arXiv.org] in 1991. In the spirit of the Web original purpose, sharing a digital version of research articles before their formal publication has rapidly become the norm in this discipline. What may come as a surprise to contemporary researchers is that correspondence between scientists to collect feedback on one's work before formal publication has always existed. In fact, following the steps of the physics community, biologists also attempted to adopt preprints mailing lists in the 1960s although in did not succeed at the time [12]. Their recent growing popularity, in particular in biology [13] and chemistry [14], may be in part related to an increase in the number of interdisciplinary projects over the past decades. Researchers who have been trained as physicists or mathematicians started contributing to research in genetics and genomics, systems biology, biophysics, molecular simulations and other subfields. In this important case of cross-pollination between disciplines, biology preprints were initially submitted to a sub-section of arXiv – called *q-bio* (arxiv.org/archive/q-bio) for "quantitative biology" – before the creation of *www.bioRxiv.org*.

Beyond publications, the potential of data sharing has recently gained the attention of the field of particle physics. In a key move, the Compact Muon Solenoid (CMS) experiment, one of two large detectors built on the Large Hadron Collider (LHC) at CERN, made three data releases in November 2014, in April 2016 and in December 2017. Anyone can now explore the data with their own point-of-view, bringing diversity in interests and skills. This allowed MIT researchers to make new discoveries, independently from the team based in Geneva [15].

It is important to realize that allowing others to reuse information is only one of the two sides to the reproducibility coin. This main motivation to produce reproducible results rests on the idea of "Nanos gigantum humeris insidentes" (dwarfs standing on the shoulders of giants) to use a popular metaphor attributed to 12th century French philosopher Bernard of Chartres. But the ability to hand over a methodology from one person to another in a timely and efficient manner enables project integrity as personnel changes over time. In a very pragmatic move, CERN needs to make sure the data it produces will not become obsolete. As pointed out, "*data and the knowledge needed to interpret them are more likely to survive in the long term if many people outside an experiment are constantly trying to make sense of them.*" [16] But open is not enough [17]. Significant efforts must be invested in careful documentation, the development of standards as well as classification methods. In fields that lack such best practice, a substantial investment and a cultural change are required, demanding efforts from every stakeholders of the research ecosystem (see Figure 1).

Fig 1. Support necessary for the cultural change leading to open science (adapted from original work by Brian Nosek, Center for Open Science [18])

But even within the physics community, there are different cultures. On the one hand, researchers using facilities – the Hubble telescope or a synchrotron beam line - compete for instrument time and collect data they often can keep under embargo. On the other hand, participants to an experiment – the Sloan Digital Sky Survey [19] or the Gaia space observatory [20] for example – participate to the construction of an infrastructure that will release data openly to all. In this case, it is the originality of their analyses that will be advantageous. For theorists or experimentalists having their own infrastructure, there is no particular incentive to participate in a collective endeavor. In each of these groups, the relationship between the researchers and the data is therefore different and collaboration between these cultures can lead to friction. We can ask ourselves why astrophysics and particle physics have been amongst the most open research disciplines. One possible answer is that there is only one sky, and there is also only one Large Hadron Collider. In

"Big Science", researchers have to mutualize resources and share outputs amongst consortia. As more and more disciplines adopt a team science strategy, openness becomes increasingly justified.

Open Science at EPFL

Because one of the missions of EPFL is to perform world-class research and disseminate the resulting knowledge and technologies as broadly as possible, there is a strong interest in exploring the potential of open science. In a world where science is increasingly international, and where interdisciplinarity and collaboration have demonstrated significant impact, our researchers have a strong incentive to share information in order to maximize their impact on the research of others, and on society at large. To some, open science may seem like a nebulous term, with philosophical, rather than practical, implications. While some initiatives explore practices that have not yet gathered consensus, others have now demonstrated value in supporting high quality research results. As research communities adopt new standards, we need to support our researchers when adopting these practices so that they stay competitive.

Since October 2017, a strategic committee is exploring the topic and how to support researchers best. It is composed of faculty members representative of the many disciplines present on EPFL campus, as well as central services providing support with issues related to open science. This committee has now made a series of recommendations on how to best leverage existing central services and resources to foster change, including a need for communication, training and new types of infrastructures.

Based on these recommendations, the EPFL Presidency has decided to dedicate resources in the form of an Open Science Fund [21]. This competitive funding will support projects that explicitly aim at increasing the use of tools and best practice in research management, as well as lowering the technical, social, and cultural barriers that make it hard for researchers to openly share some of the research outputs with their colleagues, and ultimately with anyone outside of the academic community. The fund will support projects leading to the development and bottom-up adoption of innovative ways of making research robust, accessible and reusable at any stage of the research life cycle. They should facilitate the curation and dissemination of valuable and original research outputs in all possible forms: scholarly publications, data files of all kinds, the associated metadata, software and hardware, experimental setups, methods and instruments, etc. with the hope that researchers will earn recognition for these outputs, in complement to their publication record.

In their 1992 article, Jon Claerbout and Martin Karrenbach wrote – with a certain optimism – that "*we are nearing a time when it will simply be the author's choice whether to keep detailed means to results confidential with the use of traditional publication or to communicate fully by using reproducible documents.*" [2] This choice is still that of the researchers, but as the technological barriers have constantly been lowered since the invention of the Web thirty years ago, it is has become difficult to justify not choosing the open and reproducible route.

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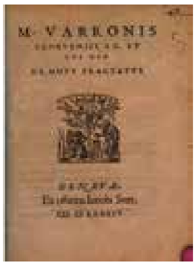
3. Internationales Jost Bürgi Symposium

Von Bürgis Uhren zur Femtosekunde – Eine kurze Geschichte der Zeitmessung

Am 3. und 4. Mai 2019 findet in Lichtensteig im schweizerischen Toggenburg im Kanton St. Gallen das 3. Internationale Jost Bürgi Symposium statt. Es soll wiederum an Person, Werk und Umfeld dieses dort geborenen Renaissance-Genies (1552-1632) erinnern, aber auch uns die Auswirkungen seines Schaffens bis in unsere heutige Zeit nahe bringen. Während das 2018 durchgeführte Symposium *Mit Bürgi zu den Sternen* auf seine astronomischen Leistungen verwies, steht diesmal mehr der erfindungsreiche Uhrenmacher im Mittelpunkt der Veranstaltung.

Workshop (Freitag 03. Mai 2019, 14 - 18 Uhr)

Im Workshop bringen wir vier Beiträge von Historikern verschiedener Fachgebiete. Zuerst wird der Präsident der Jost-Bürgi-Gedächtnis-Stiftung und Historiker **Hans Büchler**, Wattwil (Kanton St. Gallen), über *Der Eidgenosse Jost Bürgi und seine Zeit* berichten, insbesondere über das Verhältnis der Eidgenossenschaft zum Heiligen Römischen Reich.



Danach spricht der langjährige Leiter der SPG Sektion "Geschichte der Physik", **Jan Lacki**, Universität Genf, über den Juristen und Physiker *Michel Varro, A Genevan forerunner of Galileo*, der 1584 in *De motu tractatus*, einer Abhandlung über theoretische Mechanik, bereits zu Schlussfolgerungen gelangte, die die später von Galilei formulierten Gesetzmässigkeiten über den freien Fall von Körpern erkennen liessen.

Ihm folgt der Physiker und Historiker **Tilman Sauer** von der Universität Mainz mit seinem Referat *Die Prosthaphärese zwischen geometrischer Konstruktion und numerischem Algorithmus*, eines Rechenverfahrens, das als unmittelbarer Vorläufer der Logarithmen gilt, indem es die Rückführung der Multiplikation und Division auf einfache Addition und Subtraktion mittels bestimmter trigonometrischer Beziehungen erlaubt.

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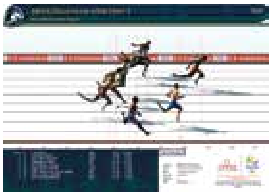
Im abschliessenden Vortrag referiert **Michael Beck** von der Museumslandschaft Hessen Kassel über *Jost Bürgis Uhren im Astronomisch-Physikalischen Kabinett Kassel*. Neben der Kalenderuhr mit Gewichtsremontoir und der „Observationsuhr“ mit Kreuzschlag und Federremontoir geht es dabei vor allem um Bürgis Mondanomalienuhr. Dieser Vortrag leitet nahtlos zum Samstagsprogramm über. Dazwischen gibt es am Freitagabend ein "After Dinner Referat" über *Technik, Kunst und Wissenschaft an der astronomischen Uhr in Stralsund aus dem Jahre 1394* von **Jürgen Hamel**, Archenhold-Sternwarte Berlin.

Symposium (Samstag 04. Mai 2019, 10 - 13 Uhr)

Der Samstagvormittag bringt zuerst zwei Vorträge zu Bürgi und seiner Zeit: **Günther Oestmann**, Technische Universität Berlin, referiert über *Zwei Hauptwerke Bürgis im Kunsthistorischen Museum zu Wien: Die "Bergkristalluhr" von 1622/27 und die ihm zugeschriebene "Planetenuhr" von 1605*, beide von ihm auf dem Prager Hradschin gefertigt. Bei der Planetenuhr handelt es sich um die welterste Uhr, die den Planetenlauf um die Sonne anzeigt, während die Bergkristalluhr, ein Alterswerk Bürgis, von ihm selbst als seine perfekteste Uhr mit eingebautem Planetenglobus bezeichnet wurde.

Danach spricht **Peter Plassmeyer**, Direktor des Mathematisch-Physikalischen Salons der Staatlichen Kunstsammlung Dresden, über *Ausgewählte Uhren aus dem Bestand des Salons*, u.a. auch über eine Jost Bürgi zugeschriebene Uhr. Der 1728 gegründete Salon ging aus der in der Mitte des 16. Jahrhunderts stammenden Kunstkammer im Dresdner Residenzschloss hervor und ist im weltberühmten Dresdner Zwinger beheimatet.

Der zweite Programmteil macht uns vertraut mit modernen Zeitmessmethoden, illustriert durch faszinierende Anwendungen aus dem Sport- und Wissenschaftsbereich:



Zuerst berichtet **Peter Hürzeler**, früherer Leiter und heutiges Mitglied des Verwaltungsrates der zur Swatch-Gruppe gehörenden Firma Swisstiming LTD, Corgémont im Kanton Bern, in seinem Referat *Schweizer Präzisionsmesstechnik im Hochleistungssportbereich* über den Werdegang der Zeit- und Längenmessung bei Olympiaden und Weltmeisterschaften von Beginn an bis heute.

Danach wird **Beat Jeckelmann**, Forschungsverantwortlicher des Eidgenössischen Instituts für Metrologie METAS, Bern, über *Zeitdefinition und moderne Zeitmessung inklusive Atomuhren* referieren. Sein auch für Laien verständlicher Vortrag wird zeigen, dass Schweizer Institutionen in der Nachfolge Bürgis stehend bei der Entwicklung modernster Messtechnik weltweit an der Spitze mitwirken.

Programmdetails auf https://www.jostbuergi.com/ .

Wissenschaftliche Symposiumsleitung: **Bernhard Braunecker**, SPG Vizepräsident und **Peter Ullrich**, Universität Koblenz-Landau (DE)

Neues Fahrzeugkonzept für urbane Mobilität

Trotz aller Fortschritte im Ausbau moderner Kommunikationsmittel wird der Bedarf an leistungsstarken Mobilitätskonzepten weiterhin zunehmen, allerdings unter Beachtung neuartiger Randbedingungen wie die der allzeit individuellen Verfügbarkeit und des ressourcen- und umweltschonenden Betriebs. Während bei den Motoren sich der E-Motor klar durchsetzen wird, besteht zurzeit noch wenig Klarheit über die optimale Technologie der Energiebereitstellung und -speicherung. Dabei ist aus politischen und kostenmässigen, sprich pragmatischen Gründen ratsam, dass vorhandene Infrastrukturen in die neuen Konzepte mit einbezogen werden. Nachfolgend ein Blog-Beitrag von *Adrian Sulzer, SATW*, der uns Physiker interessieren könnte.

BB

Das Institut für Virtuelle Produktion an der ETH Zürich hat zusammen mit der Fachrichtung Industrial Design der Zürcher Hochschule der Künste ZHdK ein innovatives Fahrzeugkonzept für Städte entwickelt. Das Resultat überzeugt nicht nur technisch, sondern auch ästhetisch. Die SATW hat die Entwicklung des Konzepts finanziell gefördert.

Expertinnen, Experten sowie Einzelmitglieder der SATW können jährlich Anträge für persönliche Projektideen einreichen. Diese passen entweder zu den Schwerpunktprogrammen der SATW oder behandeln ein anderes aktuelles, für die SATW relevantes Thema. Prof. Pavel Hora, Vorsteher des Instituts für Virtuelle Produktion an der ETH Zürich und Betreuer der Formula Student Electric Gruppe, hat 2017 einen solchen Antrag gestellt. Dabei ging es um die Entwicklung des Antriebs und Designs der Fahrzeuge im Rahmen eines grösseren Projekts zur Entwicklung eines urbanen und umweltfreundlichen Mobilitätskonzepts, das den individuellen Mobilitätsbedürfnissen gerecht wird. Entstanden ist das Konzept «Intelligent Transport Cubes – iTC» für Städte mit komplexer Topologie. Im Unterschied zur heute im Vordergrund stehenden Elektromobilität basiert es auf Brennstoffzellentechnologie, was grosse Vorteile mit sich bringt: Neben einer effizienteren Energiespeicherung und Minderung des Rohstoffbedarfes ist auch die erforderliche Infrastruktur realisierbar.

Herausforderungen im städtischen Strassenverkehr meistern

Die individuelle Mobilität wird heute weitgehend durch Automobile abgedeckt. Hohe Schadstoffemissionen, dichter Stadtverkehr und zugeparkte Strassen sind die Folge. Der weltweite Trend der Urbanisierung und steigende Mobilitätsbedürfnisse dürften diese Probleme künftig weiter verschärfen. Somit braucht es neue Mobilitätskonzepte für Städte, welche die Kapazität der bestehenden Infrastruktur erhöhen – möglichst emissionsfrei und ressourcenschonend. Beim Ersatz von Verbrennungsmotoren stellt sich natürlich die Frage der Energieerzeugung: So ist ein Elektrofahrzeug nicht umweltfreundlicher als ein Dieselfahrzeug, wenn der für den Betrieb nötige Strom vornehmlich aus fossilen Energieträgern stammt. Zudem ist die Fertigung grosser Batterien mit enormen CO_2-Emissionen behaftet. Bei der Sonnen- und Windenergie besteht wiederum das Problem der Speicherung. Aufgrund der begrenzten Verfügbarkeit von Metallen wie Kobalt, Nickel und diversen seltenen Erden haben sich die ETH-Forschenden unter der Leitung von Pavel Hora gegen eine reine Batterie-Lösung entschieden, wie derzeit von der Automobilindustrie favorisiert. Stattdessen basiert ihr Antrieb auf einem bereits heute realisierbaren Brennstoffzellen-System (Polymerelektrolytbrennstoffzelle PEMFC) mit synthetisch hergestelltem Wasserstoff (H_2) als Speichermedium.

Entwicklung des Antriebs

Für ihr H_2E-Antriebskonzept haben die Forschenden verschiedene Anforderungen errechnet, die sich an der europäischen Gesetzgebung für bestehende Fahrzeuge orientieren sowie an den Rahmenbedingungen des Grossraums Zürich. Neben der CO_2-Neutralität ergaben sich somit präzise Anforderungen bezüglich Abmessung, Betriebsbedingungen, Kapazität und Reichweite der Fahrzeuge sowie Geschwindigkeits- und Höhenprofil. Das Antriebsmodul besteht aus einer Kombination der H_2-Energieversorgung mittels Brennstoffzellen und dem Elektroantrieb. Somit handelt es sich um H_2E-Fahrzeuge mit Batterie. Im Unterschied zu Elektrofahrzeugen hat sie aber nur die Funktion eines Zwischenspeichers und ist somit viel kleiner. Weitere Komponenten sind die Wasserstofftanks, eine komplexe Systemsteuerung, welche die Energieversorgung regelt, sowie Elektromotoren, platzsparend in den Radnaben verbaut. Die Module sind so angeordnet, dass in der Mitte ein möglichst grosser «Transport Cube» Platz findet.

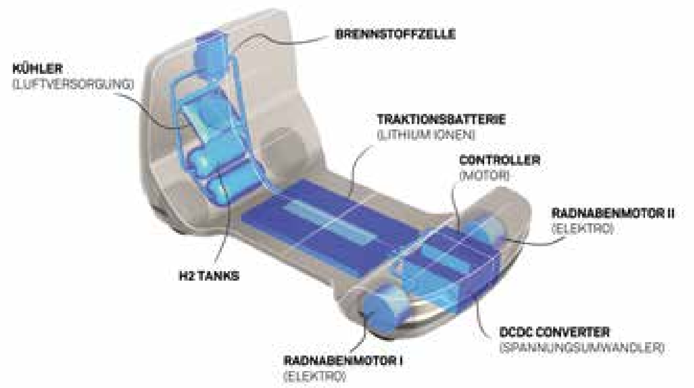


Bild 1: Anordnung der Komponenten des Antriebs. Die Motoren sind im Rad eingebaut. (Bild: ZHdK Industrial Design)

Interdisziplinäre Zusammenarbeit

Während sich die ETH-Forschenden auf die technischen Aspekte konzentrierten, entwarf Claudia Polli, Studentin an der ZHdK, im Rahmen ihrer Bachelorarbeit das Industriedesign. Wichtigste Anforderung war die Nutzung der Fahrzeuge als «Shared Service» zum Transport von Personen und Waren. Aufgrund der unterschiedlichen Nutzerszenarien entschied man sich für einen modularen Aufbau und eine Trennung von Antrieb und Kabine. Das Antriebsmodul kann also sowohl Personen- wie auch Cargomodule transportieren. Aus Sicherheitsgründen und zur einfachen Wartung ist die Wasserstofftechnik von der Kabine getrennt und von aussen zugänglich. Da für den autonomen Betrieb weder Pedale noch Steuerrad nötig sind, bestand für den Innenraum grosse Gestaltungsfreiheit. «Das Design soll Vertrauen schaffen», so Claudia Polli. «Antriebsmodul und Kabine ergeben gemeinsam eine möglichst ‹smoothe› Form, ein in sich geschlossener, ruhiger Körper. Scharfe Kanten und starke Trennungen wirken aggressiv und könnten davor abschrecken, ein solches Fahrzeug zu nutzen. Der Unterschied zwischen Cargo- und Personenmodul soll klar ersichtlich sein und trotzdem soll man sehen, dass sie aus der gleichen Familie stammen.» Die Bestellung eines iTCs erfolgt mittels App. Personen können das iTC als Taxi bestellen, für Sightseeing-Touren buchen, als Transportmittel für ihren Umzug oder um Waren autonom zu einem bestimmten Abgabeort zu senden. Praktisch alle denkbaren Nutzungen sind dank modularem Aufbau abgedeckt.

Bild 2: Überzeugendes Design gekonnt inszeniert: Fotorealistisches Rendering der iTCs (links: Personenkabine, rechts: Cargomodul) unter dem Bahnviadukt neben dem Toni-Areal in Zürich. (Bild: ZHdK Industrial Design)

Ist die Technologie schon reif?

Werden iTCs schon bald auf Zürcher Strassen verkehren? «Viele bisherige Prognosen punkto Elektromobilität oder Brennstoffzellenfahrzeuge erwiesen sich als zu optimistisch», so Pavel Hora. Das liege aber weniger an der Technologie als an den Erfolgsaussichten für die Autoindustrie und der Akzeptanz der Kunden. «Allerdings sind die Fertigungskosten für Brennstoffzellenantriebe noch zu hoch. Da sind wir als Ingenieure gefordert!» Pavel Hora erwartet, dass PEMFC und die anderen Komponenten des Antriebs mit hohen Stückzahlen künftig viel günstiger werden. Eine wichtige Rolle spiele die Industrie als Zulieferer. Doch haben wir in der Schweiz den Anschluss bei der Brennstoffzellentechnologie nicht schon verpasst? «Es ist klar, dass insbesondere Deutschland die Entwicklung neuer Fahrzeugantriebe massiv staatlich fördert», gibt Pavel Hora zu bedenken. Er und sein Team entwickeln mit einem Industriepartner die Fertigungstechnologie für die im PEMFC verbauten Bipolarplatten. Eine markante Produktionssteigerung und Kostensenkung seien da absehbar. Man könne hierzulande in vielen relevanten Bereichen wie Elektromotoren oder Energiemanagement auf Spitzentechnologien zurückgreifen und stehe der deutschen Industrie in nichts nach. «Warum denken wir nicht über eine ‹grüne› Automobilindustrie in der Schweiz nach?», fragt der Professor provokativ.

Gesamtheitliche Lösung gesucht

Im Rahmen des Projekts wird nicht nur ein Fahrzeug entwickelt, sondern ein Gesamtkonzept, das Mobilität gekoppelt mit Fragen zur Infrastruktur und Energieversorgung betrachten. Da wir den CO_2-Austoss global kurzfristig senken müssen, sind nur technisch verfügbare Lösungen anwendbar. Wie eine BFE-Studie bereits 2013 aufzeigte, ist in der Schweiz kurzfristig eine Wasserstoffversorgung für 50‘000 Fahrzeuge mit einer Fahrleitung von 15‘000 km realisierbar. Beim Aufbau von H_2-Tankstellen rechne man heute mit rund 1,2 Mio. CHF pro Säule. Da das Tanken von H_2 nicht viel anders ablaufe als bei Benzin, könnten die Tankstellenbetreiber ihre Infrastruktur weiter betreiben. Wichtig für den Endverbraucher ist die Tatsache, dass heute 1 kg Wasserstoff rund 10 Franken kostet und man damit rund 100 km weit kommt. «Verbraucher müssen ihr Verhalten nicht ändern und fahren trotzdem ohne CO_2-Austoss.» Reine Elektromobilität bedeute dagegen eine Auslagerung der Probleme auf andere Ebenen. «Das von uns entwickelte Konzept ist eine umsetzbare Alternative!»

Auskunft

Prof. Dr. Pavel Hora, Institut für virtuelle Produktion, Tel. 044 632 71 98, pavel.hora(at)ivp.mavt.ethz.ch

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Creating Personal Playlists using Artificial Intelligence

News from Schweizer Jugend Forscht, La Science appelle les Jeunes

Marianne Begré, Schweizer Jugend Forscht

What initially started as just a personal need, ended on stage at the EUCYS 2018, the EU Contest for Young Scientists (*https://eucys2018.com*).

Tobia Ochsner had a problem: there were an almost unlimited number of songs waiting for him to listen to on his Spotify playlist. The young man started to wonder how he could find the best new songs to listen to and at the same time find the hidden gems. Tobia was preoccupied by these thoughts when he was supposed to be concentrating on finding a topic for his high school project at the Kantonsschule Schaffhausen. In hindsight the solution was so obvious: why not turn the playlist problem into the school project?
Tobia started to tackle the problem by building an artificial intelligence algorithm, which would generate playlists on a given song. Ideally the AI would get to know which music

Tobia likes and then find new songs he would also probably like. Tobia built his AI using a - so-called - neural network methodology. To create and train the neural network, he wrote a framework using Python and used 1961 playlists published on Spotify with nearly 50000 songs as training data.

Take your heart!

After a lot of trial and error, he presented his near-complete work to his teachers. The teacher looked over the work and asked: “Why don`t you take part in the Swiss Youth Research Foundation (Schweizer Jugend Forscht - SJF) (*https://sjf.ch*) national contest?” The SJF competition invites 100 young Swiss scientists to present their projects to experts and the general public across three days.

So Tobia sent the SJF his novel individual-song playlist generator. The project had to pass through the preliminary competition to then be invited to a pre-workshop. At this workshop Tobia got to meet and work with several experts who helped him put the finishing touches in place.

Then the impossible came true for Tobia: an invitation to attend the national contest 2018 arrived! In May this year, Tobia and 100 other young scientists travelled to Neuchâtel to take part in the three days of competition, develop new friendships and hold important talks with experts in his specific research field.

What award will it be?

When the moment for the long-awaited award ceremony arrived, Tobia was seriously nervous; what feedback would he and his work receive? He held his breath waiting for the announcement by Dr. Yulia Sandamirskaya, his SJF expert during the national contest. Dr Sandamirskaya said “We are impressed by the care taken in problem analysis and the search for solutions as well as with the sound mathematical understanding of neural networks in one special project. Please welcome to the stage, Tobia Ochsner. Tobia you are being awarded our highest honour called ‘Superb’ and the opportunity to present your project at the European Union Contest for Young Scientists in Dublin this year.” The EU competition in Dublin is organised by the European Commission in cooperation with the host country. This year, 135 young researchers from 39 countries presented a total of 88 research projects in ten competition disciplines.

Tobia Ochsner at the SJF contest, receiving his certificate from SJF repesentative Yulia Sandamirskaya.

Welcome to Dublin

Two other Swiss researchers won the EUCYS2018-participation at the National Contest 2018 alongside Tobia in Dublin. Sébastien Garmier competed with his project “cuRRay: CUDA-Raytracer for light beams in relativistic Kerr-Newman space-time” and Luisa Stöckli with her project “Methodology for the Quantitative and Qualitative Assessment of the Microbiome in Human Tonsils”. Together the three future scientists presented and competed with the best of their contemporaries at European level and had the opportunity to meet others with similar abilities and interests.

Sébastien Garmier, Luisa Stöckli and Tobia Ochsner at the EUCYS 2018 contest.

The young researchers selected and sponsored by SJF convinced the expert jury once again and asserted themselves at European level winning three special prizes. Tobia won two special prices: an invitation to attend a week-long summer school in Bulgaria; and a visit to the INTEL Isef Exhibition 2019 in Phoenix, Arizona to further develop his mathematical understanding.

I came here to win this prize

Sébastien, a passionate amateur astrophotographer, said he had always wished for the prize he’d won. Sébastien is invited to attend a programme next year in Chile at the European Southern Observatory (ESO) - the most productive astronomy observatory in the world. He will even be able to take an exclusive look at the newly planned 39-meter-diameter "Extreme Large Telescope" (ELT), also known as the "world's largest eye in the sky".

Luisa also did an excellent job of presenting her project and mastered the competition with flying colours. The jury noted they almost couldn't believe Luisa was conducting research at such a high level.

We can be proud of Tobia Ochsner, Sébastien Garmier and Luisa Stöckli as their achievements are at the forefront of strong competition from Europe and other countries including China, Canada and the USA.

Review: Einstein Lectures 2018

Hans Rudolf Ott, ETH Zürich

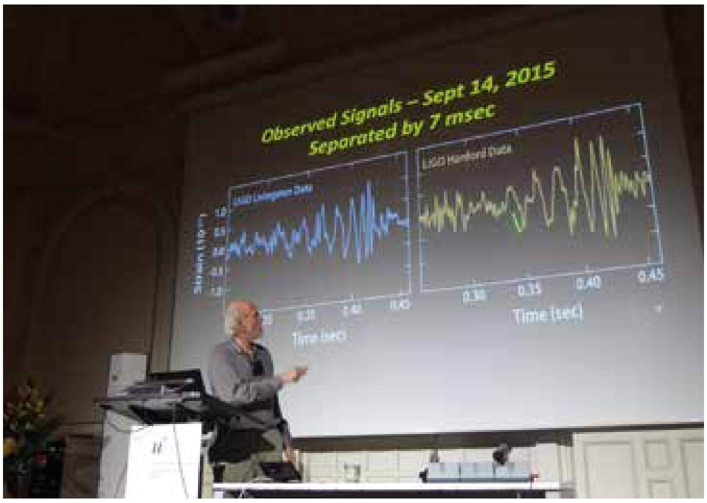
Since their inauguration in 2009, the organization of the Einstein Lectures in Bern is a collaborative effort of the Albert-Einstein Society (AES) Bern and the University of Bern. As a memento of the life and work of Albert Einstein whose scientific and academic career took off in Bern, they consist of three lectures during one week each year, usually in November or early December, on a topic alternatingly chosen from the fields of Physics and Astronomy, Mathematics, and Philosophy. While the choice of Physics, Astronomy and Mathematics is probably obvious, the inclusion of Philosophy may need some explanation. Einstein's first contact with philosophy has to be traced back to the time he spent in Bern where, in the realm of the short-lived Akademie Olympia, Einstein and his friends Conrad Habicht and Maurice Solovine, nota bene a student of philosophy at the University of Bern, read and discussed a number of philosophical writings. Later, as a world famous figure, Einstein's contacts and interactions with leading philosophers were numerous.

This year's topic was Physics and the three lectures on November 12, 13 and 14 were devoted to Gravitational Waves (GW), first directly observed on September 14, 2015, almost 100 years after Einstein's prediction of their existence, based on his still very young *Theory of General Relativity*, in June 1916. The invited lecturer was Barry Barish from the California Institute of Technology who shared the 2017 Nobel prize with Kip Thorne, also at CalTech and recipient of the Einstein medal of the AES in 2009, and Rainer Weiss from MIT for their work that led to the discovery cited above.

The first lecture, entitled *From Einstein to Gravitational Waves*, started by reminding the audience of Isaac Newton's great leap forward with his theory of gravitation in 1687 and, more than 100 years later, the experimental verification of the universality of gravitation in a laboratory experiment by Henry Cavendish who, amazingly, obtained a numerical value of the gravitational constant to within 1% of the present-day value. The validation of Newton's theory on the astronomical scale was due to Urban le Verrier who, on the basis of calculations, recognized a discrepancy between the observed orbit of Uranus and the laws of Kepler and Newton. This prompted him to predict the existence and position of a new planet (Neptune) in 1846. His prediction was immediately verified by an astronomical observation within 1 degree of the predicted angles. Four years later, Le Verrier also noted a small inconsistency between Newton's theory, and the observed elliptical orbit of Mercury. This effect, termed *the perihelion shift of Mercury*, although qualitatively consistent with Newton's theory but not quite so numerically, later played a significant role in Einstein's creation of the general theory of relativity, including his early discussion on the bending of light by gravitation already in 1907 while still in Bern. Up to this point, Newton's theory was regarded as highly successful albeit with some deficencies that called for clarification. Although Einstein was aware of these facts, he was more driven by doubts with respect to conceptual deficits which resulted in his subsequent work on general relativity and gravitation, completed in November 1915 in Berlin. It took care of the mentioned problems automatically. After having set the stage, the history of the topic of GW was briefly recapitulated, including the first conjecture of GW by Einstein in June 1916 and the later correction of the calculations in 1918. Later, after almost 20 years, Einstein and Rosen, then at Princeton, submitted an article entitled *Do Gravitational Waves exist?* to Physical Review in 1936. After some quarreling related to the refereeing process as such, at the time unknown to Einstein, and an error in the calculation, the paper was rejected and a completely revised manuscript *On gravitational waves* by the same authors, was then accepted by the Journal of the Franklin Institute. After again 20 years of uncertainty, the question of the reality of GW was answered positively at the Chapel Hill Conference on *The role of Gravitation in Physics* in 1957. It was agreed that GW can transfer energy and, with this blessing of theorists such as Biondi, Pirani and Feynman, experimentalists were now encouraged to go out and look for them.
It was soon realized that the approach to create GW sources and to detect the emitted radiation in a laboratory would not succeed because of the extremely low value of the „gravitational constant". It was agreed that the only viable option was the detection of GW emitted from cosmological and astrophysical sources. After a brief description of the pioneering work in the 1960ies of Joseph Weber who employed resonating bars cooled to very low temperatures as detectors but, in the end failed to achieve an undisputed detection of GW, the first indirect evidence for the existence of GW by monitoring the rate change of the orbital period of a binary pulsar due to the emission of GW by Joseph Taylor and Russell Hulse, both Nobel laureates in 1993, was mentioned. Incidentally, Taylor was awarded with the Einstein medal of the AES in 1991, i.e., before receiving the Nobel prize. The final part of the first lecture summarized the story of the monitoring of spacetime ripples by suspended-mass interferometry. As an example, the creation of such ripples by a merger of binary black holes (BH) was considered and illustrated, followed by presenting and briefly discussing the finally successful observation of signals from a BH merger, approximately 1.3 billion years ago, at the two US GW observatories of the LIGO collaboration in Livingston (Louisiana) and Hanford (Washington) on September 14, 2015.

The content of the second lecture on *Gravitational Waves from Detectors to Detection* was devoted to explaining what it takes to reach the necessary resolution in measuring relative length changes $\Delta L/L = h$ that indicate the passage of a GW through a suspended-mass interferometer. The essential parts of the interferometers such as test masses, mirrors, lasers and their limitations with respect to noise were discussed. It turns out that spacetime is very stiff and therefore, the expected distortions and hence the induced variation of the distance between two free-to-move masses is very small. The design value for the LIGO observatories was set to $h = 10^{-21}$ which typically allows to provide evidence for the merger of a binary BH of 30 solar masses at a distance of 500 Mpc. With the actual value of 4 km for the length of an interferometer arm, ΔL of the order of 10^{-18} m may be resolved. Noting that the diameter of a proton is approximately 10^{-15} m, the attempted and obviously achieved resolution is really remarkable. Naturally an essential task in the design, construction and operation of the interferometer is to separate the signal from those generated by the many sources of noise inherent in the earth system. Important for the performance of the observatory is the huge number of photons in the laser beams that traverse the arms of the interferometer and help to improve the statistics of the experiment. Barish also addressed the development of the instruments and briefly described and discussed some signals from monitored merger events since 2015.

A significant step forward with respect to the determination of the direction of the incoming GW was made by including the also functional but smaller VIRGO observatory near Pisa in Italy in the observational campaign in 2017. A more recent but particular highlight was the first observation of GW due to a binary neutron-star merger involving substantially lower masses than in BH mergers but with the accompanying emission of electromagnetic radiation which was identified by many alerted observatories, thereby opening the window for multi-messenger astronomy with GW. The last foil of this lecture compared the recorded data with the prediction of general relativity calculations for a BH-merger signal.



The third lecture on *Gravitational Waves and a Future New Science* first repeated parts of the two previous lectures, intended to pave the way for a discussion of expected new opportunities in observing fundamental events that occurred during the expansion of the universe far back in time and hence far out in distance. The new approach is termed *multi-messenger astronomy* with gravitational waves accompanied by signals across the electromagnetic spectrum including radio waves, the infrared and visible regime, up to x-rays and gamma-rays, complemented by showers of neutrinos. While the GW signals reflect the emission of GW within only a short time span of the order of seconds or fractions thereof before and rapidly changing their frequency close to the merger, the electromagnetic-wave signals may be monitored during a distinctly longer time period, up to days. Theoretical modelling indicates that this radiation is due to the radioactive decay of isotopes that form at the merger by a process known as rapid neutron-capture (r-process) nucleosynthesis. The thermally induced radiation emitted from this *kilonova* may be used to identify the products of the r-process and it has been found that, e.g., the precious metals Au and Pt are among them. Large portions of heavy elements in the periodic table beyond Fe have their origin in mergers of neutron stars, another important conclusion from this first observation of this type of event. Details of the GW signals are expected to reveal the origin of BH.

Barish then described the technical development for a full exploitation of the LIGO sites by technological improvements concerning the test masses and the lasers towards an enhancement of the cosmological reach, an improved s/n ratio and thus a higher rate of observed events. The layout of future observatories such as the Einstein telescope, a European enterprise, will likely be installed underground with longer arms in a triangular configuration and cryogenically cooled detector elements. In this way it is expected to enhance the present LIGO sensitivity by a factor of 10. Apart from discussing the improvement of the performance of earth-based GW observatories and mentioning new instruments such as KAGRA in Japan and LIGO India, expected to go into operation in 2019 and 2025, respectively, a brief outlook on a space-based mission of a GW observatory, the laser interferometer space antenna (LISA) of the European Space Agency (ESA) was presented. This instrument consists of 3 interferometers with an impressive armlength of 2.5 Mkm. The recent mission *LISA pathfinder*, aiming at demonstrating the potential for success of the chosen technology, was successful. The installation and operation of the planned observatory is foreseen around 2035. Another project, aiming at observing the influence of GW on the time component of spacetime is based on the periodic emission of electromagnetic radiation by pulsars which can be interpreted as highly accurate clocks. Many collaborations around the globe are involved in monitoring this effect in the realm of the *pulsar timing array* (PTA). This experimental approach is sensitive to events in the very low-frequency regime.

The presently known astrophysical sources for GW may be characterized by their signal signatures. The compact inspiraling binaries appear as chirps (the rapid enhancement of the inspiralling frequency just before the merger). The particular characteristics of supernovae and gamma-ray sources is the emission of GW bursts which are announced by preceding neutrino showers. A third class are periodically emitting sources in our galaxy (pulsars) and a fourth class are cosmological signals which form a stochastic background, in some sense the analogue of the cosmic background radiation (CMR). Monitoring such GW signals and their interpretation seems to be the only way to get information from events that happened in the very early universe and therefore are a very attractive challenge to be addressed in future research. Future detectors and the respective data analyses need to be adapted to the monitoring of these sources.

The last foil of this lecture and thus of the entire 2018 EL series reminded the audience of the beginning of observational astronomy with optical instruments by Galilei and compared it with today's situation, i.e., the beginning of a new era of observational astronomy and astrophysics using gravitational waves.

Report about the Symposium "Richard Feyman's centennial celebration"

Jan Lacki and Hans Peter Beck

On November 30th the Swiss Physical Society and the History and Philosophy of Science Unit of the Geneva University jointly organized a one day celebration of Richard Feynman's 100th anniversary. The organizers endeavored to call to mind some of Feynman's most famous contributions to 20th century physics and to show how his ideas are alive and continue to inspire in contemporary research.

Richard Feynman's centennial celebration

Program

Olivier Darrigol (CNRS, Paris VII)
The magic of Feynman's QED

Adrian Wüthrich (TU Berlin)
Putting Feynman's style into context

Charalampos (Babis) Anastasiou (ETH Zürich)
Feynman diagrams and modern collider physics

Gabriele Veneziano (CERN, Collège de France)
Feynman's strong interaction side

Uwe-Jens Wiese (Universität Bern)
Quantum Simulation: Feynman's Vision

November 30th, 2018, 10:00h – 17:00h
Sciences II – Auditorium A100
30, quai Ernest Ansermet, Geneva

https://indico.cern.ch/e/feynman_centennial
Free entrance, no registration required

Organisation
Hans Peter Beck (Universität Bern), Jan Lacki (Université de Genève),
Claus Beisbart (Universität Bern), Christian Wüthrich (Université de Genève)

SPS swiss physical society
UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES

The Morning Session

The morning session started with a short presentation of the day by Hans Peter Beck and Jan Lacki. The president of the Physics department, Prof. Dirk Van der Marel welcomed next the audience and emphasized the pervading role of Feynman physics in contemporary research.

The session opened its scientific part with two presentations devoted to a historical analysis of the work of Feynman and especially of the circumstances which made him obtain his best known results in QED – expressed in terms of his highly idiosyncratic algorithmic of diagrams.

Olivier Darrigol from CRNS-Paris VII proposed a very detailed analysis of the road that led Feynman to formulate his "space-time" approach to quantum electrodynamics. He first reminded the audience that the starting point of Feynman, when still a doctoral student, was the ambition to obtain a theory where one could dispense with fields (the latter were judged responsible, because of self-interaction of charges, of the severe divergences met in the computation of such effects as the Lamb shift). With the help of his Princeton Ph.D. advisor John Archibald Wheeler, Feynman developed a classical formalism based on action at a distance (albeit with advanced and retarded potentials). However, the quantization of this theory was problematic as it was formulated only with the help of an action function deprived of a Hamiltonian foundation. This is where Feynman invented a novel approach to quantization based on what we call today path integrals. The outcome of the calculations made within the new method yielded eventually the combinatorics of terms that one could generate with the help of "diagrams". Feynman impressed his peers at the 1948 Pocono conference with his ease to obtain results others had so much trouble to compute. One had to wait however until his first publications on the topic (1948 and 1949) to learn his formalism. A very interesting observation is that in his first papers, Feynman did not explain the path integral rationale behind his diagrammatic approach and only exposed their "space-time" propagator logic, supposedly more "intuitive". This is probably the reason why many physicists today do not realize that the path integral technique was actually invented in direct relation to what Feynman is best known for, his diagrammatic technique as typically exposed in any introductory text book on relativistic quantum mechanics.

The intervention of Olivier Darrigol which raised numerous questions and further illuminating remarks was followed by a presentation by ***Adrian Wüthrich*** from the Technische Universität in Berlin. In spite of the fact that the content of his presentation overlapped his predecessor's, Wüthrich managed to shed further light on the circumstances that shaped the characteristic style of Feynman's approach to QED processes. The key point of Wüthrich analysis was to try to understand the origin of the kind of "modularity" characteristic of Feynman's approach to QED. According to historian Peter Galison, modularity, defined as the strategy to obtain complex solutions to problems from more elementary solutions (typically kernels or Green functions), a strategy that one can indeed clearly see at work in Feynman's QED diagrammatic approach, goes back to Feynman's wartime work in the Manhattan project where obtaining practical (numerical) answers to concrete problems was an objective much prevailing over more "fundamental" theoretical endeavors.

While partly agreeing with Galison, Wüthrich argued convincingly, relying on archival not yet published material, that one should also take into consideration the post-war failure of Feynman to derive a physical model of Dirac's electron going beneath and giving ultimate justification to the formal approach of the action function used in path integration. Because Feynman met difficulties within his candidate microscopic model (inspired by earlier attempts by Breit and Schrödinger to fancy a light fast oscillating particle), when he considered interaction, he eventually gave up such attempts and consequently he decided to remain content with a "higher" level, more formal and abstract approach that he has obtained from his action function inspired path integrals. Wüthrich offered thus a complementary view on the origin of Feynman's "space-time" approach as developed in his 1948 and 1949 founding papers.

The Afternoon Session

The afternoon session contained three contributions. ***Charalampos (Babis) Anastasiou*** started first, discussing *Feynman diagrams and modern collider physics*. Anastasiou is a theoretician from ETHZ and best known for his contributions to high-precision cross-section calculations, which also brought him the Latsis Prize for his significant contributions to the phenomenology of particle physics and perturbative quantum field theory.. Anastasiou highlighted in his talk the role which Feynman diagrams play when understanding collision events at high-energy proton-proton colliders, and went in particular in their eminent role for the Higgs discovery that was achieved at the LHC back in 2012. The Feynman rules, according to Anastasiou are indeed the letters in the alphabet of physics. However, when calculations are needed at a high precision, the complexity when calculating a specific process grows quickly. While only a single diagram is sufficient to calculate a process at first order, the next higher order will already involve order of ten diagrams to consider, and this number grows fast to an unimaginable few million diagrams to calculate already at fifth order perturbative expansion. Handling these, and proofing the expansion series is still converging and meaningful is what is required for high precision measurements at the LHC, and these lay the basis when searching for new physics beyond the standard model.

Gabriele Veneziano, former head of the CERN theory division and best known for his formulation of string theory to describe the strong interaction, followed discussing *Feynman's strong interaction side*. Veneziano holds many awards, among the ITCP Dirac Medal, the Albert Einstein Medal, or the Pomeranchuk Prize, to name just a few. The talk highlighted Feynman's contributions to the understanding of strong interactions before QCD was becoming a firmly established theory. Feynman formulated a scaling law limiting the energy fraction a typical hadron has that is created in a high-energy proton-proton collision. Feynman scaling in hadronic physics, as well as Bjorken scaling in deep inelastic scattering prompted Feynman to propose the parton model, in which hadrons are constituted from more basic partons that behave like free particles inside a hadron. This basic idea led eventually to the formulation of QCD, where these partons are now understood as the spin-1/2 quarks, and the spin-1 gluons. Veneziano concluded with an encounter and a beer he had together with Feynman in 1979 during a conference at Caltech, where they discussed underlying dynamics of partons inside hadrons, and 'fraying jets' in hadron-hadron collisions. However, this was the only beer they had together.

The centennial celebration concluded with a presentation of ***Uwe-Jens Wiese*** from the University of Bern. Uwe-Jens' talk on '*Quantum Simulation: From Feynman's Vision to Today's Reality and into the Future*' took up from an early idea of Feynman on the ultimate quantum simulator, he originally envisioned already in 1982. Classical computing was considered not sufficient by Feynman to describe nature fully. Indeed, quoting Feynman makes this clear: "*I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.*" Wiese covered the development of modern classical computing and where it actually arrived today with the construction of early small-scale quantum computers. However, these are not yet good enough. Wiese did not stop there, but described how ultra-cold atoms, bound in optical lattices, do allow for studying quantum simulations and this way are opening up a path that will lead to a deeper understanding of quantum computing; and eventually will allow for extending our brain with computing machines.

The scientific part of the centennial celebration ended there, but the discussions continued over a beer and a dinner in a restaurant nearby, where the speakers, invited guests, and the organizers continued digesting the rich event in a pleasant atmosphere.

The symposium has been recorded on video, accessible on https://mediaserver.unige.ch/collection/VN3-2889-2018-2019-A


MFIA
MFLI
HDAWG
HDAWG
UHFQA
UHF
UHFAWG
Zurich Instruments
PQSC
Programmable Quantum System Controller