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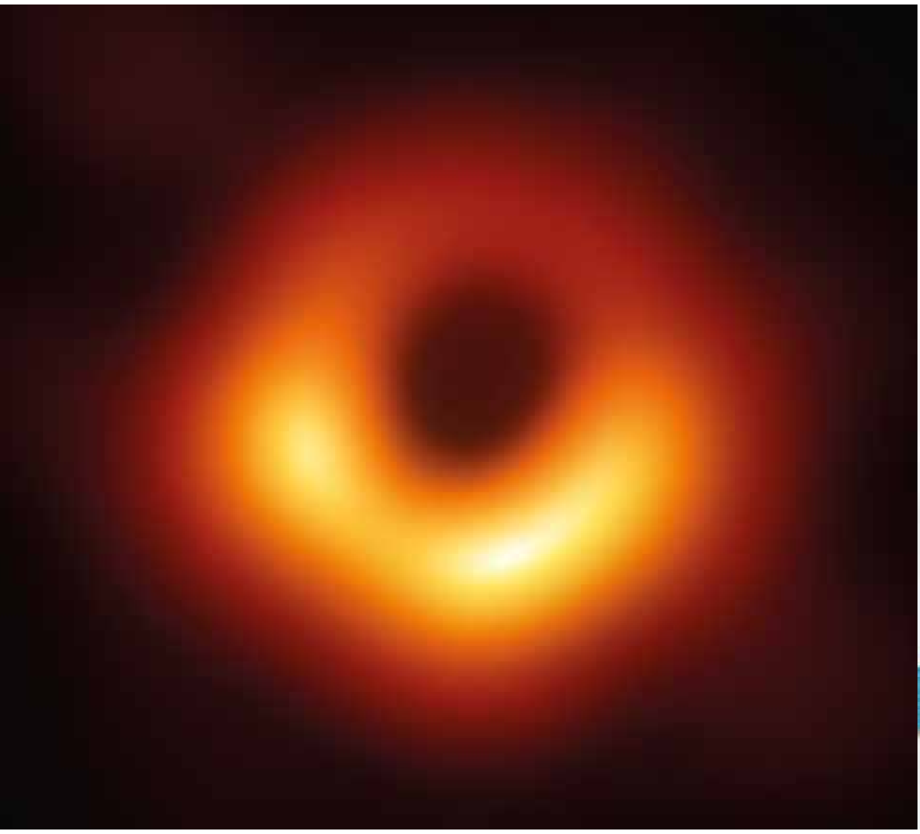
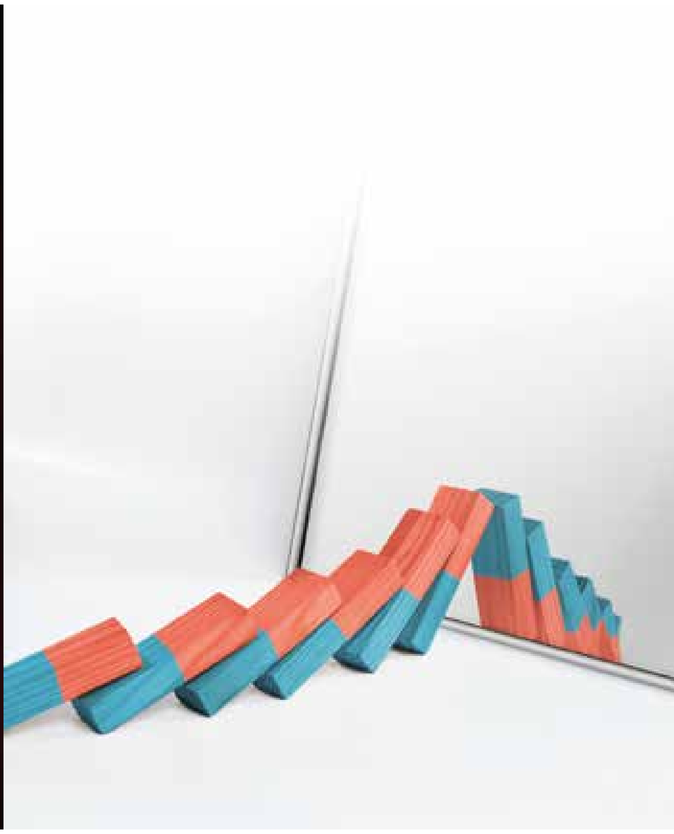


The recently taken photos from a supermassive black hole in the center of the giant galaxy M87 are a milestone in the evolution of black hole physics. Please read more about its history starting more than hundred years ago on p. 38.



As an analogy to the unique handedness in chirally-coupled mesoscopic magnetic systems, the chirality of bar magnets falling towards a mirror is kept on the other side of the mirror with an optical illusion. More on p. 34.

This year's award winners (from left to right): Maksym Serbyn (ÖPG Boltzmann Award), Michał Rawlik (CHIPP Award), Amir H. Ghadimi, Matteo Fadel, Shadi Fatayer, Ileana-Cristina Benea-Chelmus, Edoardo Baldini (SPS Awards), Minh Quang Tran (Chair of the SPS Award Committee), Alain Fontaine (SFP representative), Benoît Deveaud (Charpak Ritz Award), Hans Peter Beck (SPS President). Details on p. 4.

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Editorial

Putting Physics to Work

Thilo Stöferle, Andreas Fuhrer

For many physics students, a job in academia is their dream career. However, only a small fraction will be able to actually follow this path due to the very limited number of permanent positions in this sector. As upsetting as this may seem to the individual at first, it is not a bad thing. There are plenty of exciting jobs for physicists out there. Sometimes they are in areas where it is obvious such as research divisions of large technology companies, sometimes more hidden as for example in a startup that develops cutting-edge scanning probe microscopes for applications as seemingly remote as potato sorting.

As SPS section heads for "Physics in Industry" we strive to provide a glimpse into the wealth of opportunities that are out there after graduation from university. At every SPS Annual Meeting, we organize an afternoon session showcasing typical and atypical physics careers. It is because of the passion and enthusiasm that the speakers convey that these sessions are generally very well received, and in some cases could serve as eye-openers for Master and PhD students as well as postdocs.

This year's session about "Quantum and Artificial Intelligence – New Jobs in Emerging Industries" was not different. The focus on these two extremely "hot" topics where physicists can make important contributions resonated well. From just-hatched startups to established, mature technology companies, from sparkling junior entrepreneurs to senior research division heads, there was ample inspiration for all sorts of careers and the sometimes winding roads that may lead there. The base line: The unique mind and skill set of physics graduates is an essential asset for these rising industry ecosystems.

For those curious and eager to get hands-on experience in these two hot topics, the pre-conference workshops presented an excellent opportunity to learn how to either program a quantum processor for machine learning tasks or to program machine learning models for experimental quantum physics.

So yes, there is a life after university – and once you have taken the courage to make the step, there is a very good chance that it will be enormously rewarding and fun to shape the technologies of the future and bring them to life.

Quantum for AI and AI for Quantum Pre-Conference Workshops

A novum at the SPS/ÖPG annual meeting were the two pre-conference workshops for students, postdocs and senior researchers to get hands-on experience in coding for quantum computing and machine learning. The workshops started in the morning with two joint lectures on gate-based quantum computing and the fundamentals of machine learning applications. In the afternoon the forty participants split into two teams: Guided by Stefan Wörner, Christa Zoufal and Almudena Carrera from IBM, one team learned how to implement simple quantum machine learning algorithms on an IBM-Q quantum processor using the python-based software Qiskit. The second team worked with Professor Titus Neupert, Mark Fischer, Eliska Greplova, Kenny Choo and Frank Schindler on implementing and training their own machine learning models to predict physical properties of quantum systems.
The response from both workshops was very positive and a big thank-you goes to all the lecturers and tutors! The successful day was followed by a get-together barbecue sponsored by the IBM Qiskit Community which allowed for everyone to continue their discussions and strengthen any entanglement that happened during the day.

Pre-announcement: SPS Annual Meeting 2020

The next Annual Meeting will take place at the ***University of Fribourg***, in the week of ***29 June - 3 July 2020***. The well established tradition of collaborating every second year with the Swiss Institute for Particle Physics (CHIPP) and other partners will continue.

Save the date !

It is **your** conference, so we welcome contributions from all topical fields. The detailed announcement will be published in the next *SPG Mitteilungen*, available in early 2020, as well as on our website.

The winners of the SPS Awards 2019

The SPS Award committee chaired by Professor Minh Quang Tran selected the winners for 2019 out of many submissions. The winners presented their work at the Joint Annual Meeting in Zürich. Below are the laudations, complemented by brief summaries directly provided by the winners.

SPS Award in General Physics, sponsored by ABB

The SPS Award in General Physics is given to **Matteo Fadel** for his work on "Quantum metrology and non-classical correlations in ultracold atomic ensembles".

Quantum correlations in many-body systems: theory and experiments

Quantum correlations can be so strong that they go beyond our classical intuition. In fact, these correlations are not observed in our everyday lives in the macroscopic world: why? This question motivates the investigation of quantum correlations in many-body systems, which are interesting for both fundamental research and practical applications: they allow to investigate the validity range of quantum mechanics and they are a resource for tasks that are inaccessible by classical means.

Three different types of nonclassical correlations have been identified, namely entanglement, Einstein-Podolsky-Rosen (EPR) correlations, and Bell correlations. Preparing and observing such correlations in many-body systems is challenging. Some of the difficulties lie in the complexity of manipulating fragile many-body quantum systems, and in the need to conclude correlations between the individually inaccessible constituents from collective properties of the system.

My doctoral thesis was devoted to the experimental and theoretical investigation of quantum correlations in many-body systems. Together with my colleagues, I reported experiments where we prepare Bose-Einstein condensates (BECs) of approximately 600 Rubidium-87 atoms in a spin-squeezed state, and analyse the correlations between the constituent atoms. The results obtained during my doctorate show how entanglement, EPR-steering and Bell correlations can be detected and characterised in many-body systems, and open new possibilities for the characterisation of multipartite quantum states. As a first major result, we derived practical witnesses for Bell correlations, involving collective measurements on the entire system, which we then tested experimentally in our BECs [1]. We show the experimental detection of Bell correlations in a BEC of approximately 500 atoms, therefore demonstrating that such correlations can be prepared and detected in many-body systems.

The concept of correlations in ensembles of indistinguishable particles, as in the case of BECs, has been discussed controversially, and its usefulness for quantum technologies other than metrology has been questioned. Therefore, as a second major result, we showed experimentally how correlations in a system of indistinguishable particles can be extracted into spatially separated (and therefore distinguishable) regions, and used to demonstrate EPR steering between two ensembles of approximately 300 atoms each [2]. Apart from being the first observation of steering between two mesoscopic systems, our result shows that the splitting of atomic ensembles in nonclassical states can be used to share quantum correlations enabling tasks such as quantum teleportation and one-side device-independent communication.

[1] R. Schmied, J.-D. Bancal, B. Allard, M. Fadel, V. Scarani, P. Treutlein and N. Sangouard, Science 352, 441 (2016)
[2] M. Fadel, T. Zibold, B. Décamps and P. Treutlein, Science 360, 409 (2018)

SPS Award in Condensed Matter Physics, sponsored by IBM

Edoardo Baldini received the SPS Award in Condensed Matter Physics for his work on "Nonequilibrium Dynamics of Collective Excitations in Strongly Interacting and Correlated Quantum Systems".

Nonequilibrium Dynamics of Collective Excitations in Quantum Materials

Unveiling the origin of exotic phenomena in quantum materials is a subject of tremendous interest for the design and control of advanced functionalities in future devices. However, the presence of strong interactions among charge, spin, orbital and lattice degrees of freedom renders quantum materials a puzzling case to understand. The most promising strategy to address the complexity of this many-body problem is revealing how the electrons in this class of solids interact among themselves and with other elementary excitations. In this respect, spectroscopy under equilibrium conditions has dominated the research in the field for decades, monitoring the energy-momentum dispersion of fundamental elementary excitations. Nevertheless, this equilibrium approach suffers from several intrinsic limitations, as it provides only a time-averaged picture of the underlying dynamics and hinders the possibility to disentangle the contributions of spectrally-overlapping excitations. Key to overcome these limitations is the design of a tailored nonequilibrium approach that can address the fundamental paradigm of quantum materials. Potentially, one needs a technique that can separate the spectroscopic fingerprints of different degrees of freedom while simultaneously mapping the low- and high-energy scales with ultrafast temporal resolution, an approach that has been lacking so far. To address this problem, here we present a novel laser-based nonequilibrium method in which the ultrafast changes in the optical spectrum of a quantum material are mapped with a time resolution of < 50 fs over an ultrabroad range. This allows for unraveling mutual couplings between distinct low- and high-energy collective modes and achieving new manipulation schemes of fundamental excitations in technology. Special emphasis will be given to the rising fields of excitonics and phononics in materials governed by strong interactions and correlations [1].

[1] E. Baldini, Nonequilibrium Dynamics of Collective Excitations in Quantum Materials (Springer, 2018)

SPS Award in Applied Physics, sponsored by Oerlikon Surface Solutions AG

The SPS Award in Applied Physics is given to **Shadi Fatayer** for his work on "High precision experiments with zeptoampere resolution using Atomic Force Microscopy".

Investigating charge-state transitions of molecules on insulating films by atomic force microscopy

The electronic properties of adsorbates on surfaces are crucial for applications in molecular electronics, photo-conversion and catalysis. Molecular devices benefit from molecules on top of non-conductive substrates, to avoid charge leakage. Experimentally, the electronic properties of adsorbates can be studied by, for example, photoemission and scanning tunneling microscopy. Yet these techniques do not allow for measurements on insulators.
Based on the atomic force microscope (AFM), we developed a method to investigate the electronic properties of individual adsorbates on insulators. We demonstrated that molecular charge states, including doubly charged states, can be both controlled and determined with the AFM. Importantly, to gather quantitative information, we developed a method to perform tunneling spectroscopy with the AFM. The AFM is employed as an ultra-low current meter based on counting single-electron tunneling events in real time [1]. The analogous currents measured are in the zeptoampere range.
In this way, we could quantify the reorganization energy of a single molecule on an insulator [1]. The reorganization energy is a crucial parameter in determining electron-transfer rates. Besides quantifying the electronic properties of single adsorbates on insulating films, our work provides insight into single-electron transfer processes and suggests ways to tune and manipulate energy transfer rates between molecules.
Moreover, we employed charge-state control to perform unconventional on-surface chemical reactions of molecules on insulators [2]. By attaching and detaching electrons from the AFM tip to the molecule we demonstrated control over bond cleavage and formation.

[1] S. Fatayer et al. Nature Nanotechnology 13, 376-380 (2018)
[2] S. Fatayer et al. Physical Review Letters 121, 226101 (2018)

SPS Award related to Metrology, sponsored by METAS

Ileana-Cristina Benea-Chelmus is honored with the SPS Award related to Metrology for her work on "Terahertz quantum optics with ultrashort pulses".

Terahertz quantum optics in the time-domain

One of the most fundamental yet peculiar concepts in quantum mechanics is the existence of vacuum field fluctuations. Owing to Heisenberg uncertainty, a fluctuating electromagnetic field is characteristic to the ground state of light even in a vacuum. The ground state contains zero photons and an intensity measurement thereof yields zero. The existence of vacuum field fluctuations was confirmed through indirect phenomena such as the Casimir force or the Lamb shift. To detect them directly, ultrafast field detectors are required.
In this work we measure, for the first time, the amplitude of these fluctuations at terahertz frequencies, and then investigate how these fluctuations are correlated across time and space [1]. This measurement gives access to their spectrum and spatial coherence - quantities that influence effects related to vacuum fields. The technique exploits the electro-optic effect introduced by the vacuum electric field in a crystal.
We demonstrate that a non-zero field coherence is reminiscent even after all classical light has been removed from the system - a clear signature of ground state properties in the quantum picture. Our results agree quantitatively with the quantum theory. This endeavor implied extreme experimental measures: the detection crystal was placed inside a closed-cycle Helium-3 cryostat to shield and suppress any classical radiation. Moreover, all elements were maximally optimised to work at the absolute quantum noise limit for measurement times > 10000 s. The field sensitivity is record-high (0.25 V/m). The technique gives unparalleled information about the coherence of vacuum fields but was first benchmarked for classical fields. The initial demonstration allowed the observation of a transition from Poissonian photon statistics to bunching in a laser system [2]. In parallel, we develop ultra-sensitive field detectors that make use of nanofabrication to open up the field to cavity electrodynamics experiments in the time-domain.

[1] I.-C. Benea-Chelmus et al., Electric field correlation measurements on the electromagnetic vacuum state, Nature 568, 202-206 (2019)
[2] I.-C. Benea-Chelmus et al., Subcycle measurement of intensity correlations in the terahertz frequency range, Phys. Rev. A 93, 043812 (2016)





SPS Award in Computational Physics, sponsored by COMSOL Multiphysics GmbH

The SPS Award in Computational Physics is given to **Amir H. Ghadimi** for his work on " Elastic strain engineering for ultra-low mechanical dissipation".

Ultra-coherent micro-mechanical resonators for quantum information processing at room temperature

Elastic strain engineering utilizes stress to realize unusual material properties. For instance, strain can be used to enhance the electron mobility of a semiconductor thin film, enabling more efficient solar cells and smaller, faster transistors. In the context of nanomechanics, the pursuit of resonators with ultra-high coherence has led to intense study of a complementary strain engineering technique, “dissipation dilution”, whereby the stiffness of a material is effectively increased without added loss. Dissipation dilution is known to underly the anomalously high quality factor of nanomechanical resonators including recently-developed “soft-clamped” resonators [1]; however, the paradigm has to date relied on weak strain naturally produced during material synthesis. By contrast, the use of geometric strain engineering techniques—capable of producing local stresses near the material yield strength—remains largely unexplored.
In this work, we show that geometric strain engineering combined with soft-clamping can produce unprecedentedly high quality factor nanomechanical resonators [2]. Specifically, using a spatially non-uniform phononic crystal pattern, we co-localize the strain and flexural motion of a SiN nanobeam, while increasing the former to near the yield strength. This combined approach produces string-like resonators with room-temperature $Q \times f$ products above 10^{15} Hz, far exceeding previous values for a mechanical oscillator of any size and any type. The devices we have realized can have room temperature force sensitivities of $\sim 1\ aN / \sqrt{Hz}$, perform hundreds of quantum coherent cycles at room temperature, and attain $Q \sim 10^9$ (1 billion) at megahertz frequencies. These results signal a paradigm shift in the ability to control dissipation in nanomechanical systems, with applications ranging from quantum information processing, precision force microscopy to tests of quantum gravity. Combining the reported approach with crystalline or 2D materials may lead to further, possibly substantial, improvements.

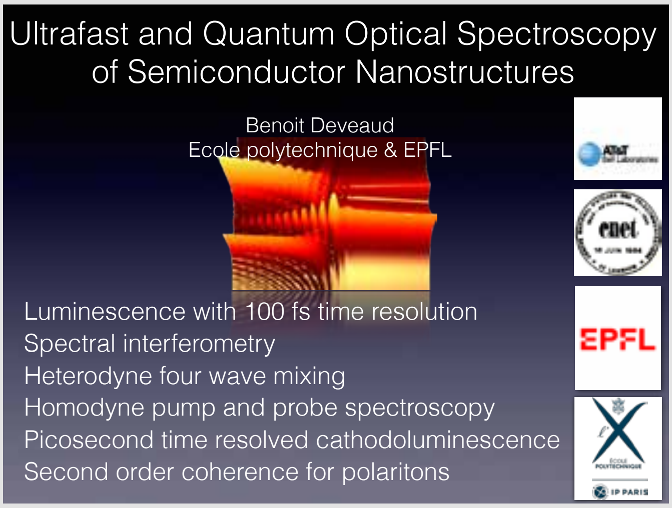
[1] Y. Tsaturyan, A. Barg, E. S. Polzik, and A. Schliesser, “Ultracoherent nanomechanical resonators via soft clamping and dissipation dilution,” *Nature Nanotechnology*, vol. 12, no. 8, pp. 776–783, Jun. 2017.
[2] A. H. Ghadimi et al., “Elastic strain engineering for ultralow mechanical dissipation,” Science, vol. 360, no. 6390, pp. 764–768, May 2018.

Charpak-Ritz Award

Benoît Deveaud is honored with the Charpak-Ritz Award 2019 for his "pioneering optical spectroscopy studies dedicated to the ultrafast and quantum optical properties of semiconductor nanostructures." A detailed laudation has already been printed in the *SPG Mitteilungen* Nr. 58, p. 27.

A brief history of polariton quantum fluids

Polaritons are half-light half matter quasiparticles resulting from the strong coupling of photons confined in a microcavity with excitons confined in a semiconductor quantum well. Polariton condensates may be created both spontaneously through a “standard” phase transition towards a Bose Einstein condensate, or be resonantly driven with a well-defined initial phase, speed and spatial distribution.
Thanks to the photonic component of polaritons, the properties of the quantum fluid may be accessed very directly, with in particular the possibility of detailed interferometric studies. This allows for example to probe the long-range coherence properties of a quantum fluid with unprecedented ease. This also allows testing superfluid properties with great precision in space and time.
In this talk, I will review the main achievements in the field of polariton physics, and try to give some perspective for future research tracks. I will show that polaritons are benefiting, through their photonic component, from a very small mass, and at the same time, through their matter component, they are able to interact. The consequences of this double nature are manyfold.



Best Poster Award 2019

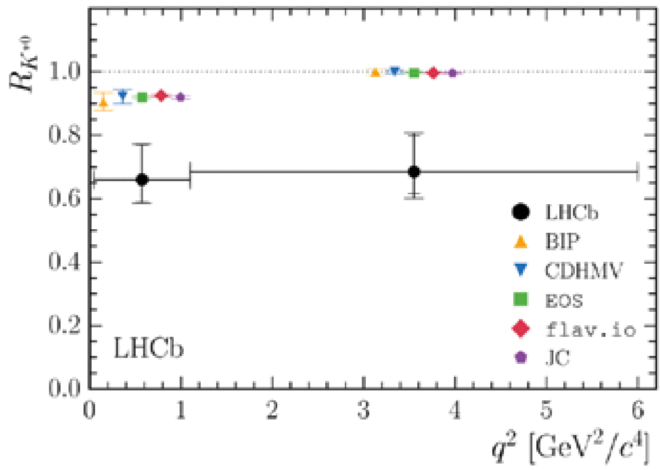
Lukas Gallmann, SPS Secretary

The three best posters presented at the 2019 joint annual meeting of the SPS and the ÖPG at the University of Zürich were awarded with the Best Poster Award. This year's prize was kindly sponsored by EPL and consisted of a certificate, a CHF 200.- cash prize (in the form of the physics related bill issued with the latest series), and the waiver of one article publication charge at EPL. A total of 61 posters competed for the award from which the jury selected the works of **Sara Celani**, **Jens Oppliger**, and **Fabio Scafirimuto** as the final winners in a two-step evaluation procedure. The winners were then invited to convey the essence of their work in a brief 2-slide presentation during the poster award ceremony on the last day of the meeting. I would like to thank the participants for the high quality of their contributions and express my gratitude to all members of the jury for their hard work during the evaluation of the posters. Namely, the members of the 2019 jury were: Andreas Fuhrer, Lukas Gallmann (jury chair), Matthias Hengsberger, Andreas Ney, Monika Ritsch-Marte, Andreas Schopper and Gottfried Strasser.

Experimental Strategy to Test Lepton Flavour Universality in $b \to s\ell^+\ell^-$ Decays in LHCb

Sara Celani, EPFL

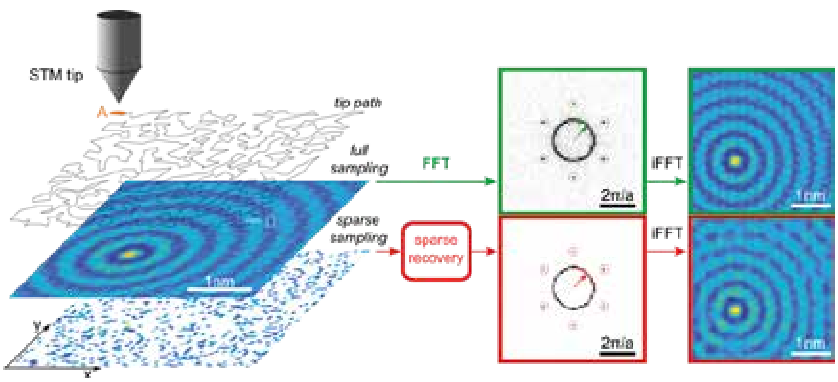
Lepton Flavour Universality (LFU) is one of the fundamental properties of the Standard Model (SM): the three lepton generations should be identical except for their masses. Flavour changing neutral current processes such as $b \to s\ell\ell$ are ideal to look for hints of LFU violation: they have small SM amplitudes, allowing sizeable contributions from hypothetical new particles.
Clean observables such as the ratio between $B \to X_s\ell\ell$ decays, with $\ell = e, \mu$ and where X_s is a strange meson, have been measured with the LHCb detector hinting at deviations from LFU. Further work on similar decays, such as $B \to K\pi\pi\ell\ell$, will allow to corroborate or disprove these deviations.



Sparse Sampling in Scanning Probe Microscopy

Jens Oppliger et al., University of Zurich

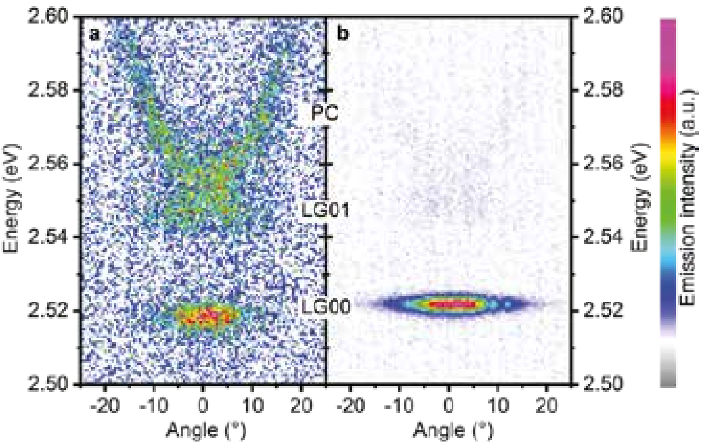
Quasiparticle interference mapping (QPI) in a Scanning Tunneling Microscope (STM) is a rather slow technique which can take up to several days of measurement time to resolve the LDOS and underlying band structure details.
Compressive Sensing (CS) is a sparse signal recovery theory which allows to completely reconstruct a signal by using just a few measurements. CS relies on the sparsity of the signal in some vector domain and on incoherent measurements. In STM QPI mapping the sparsity is given by a few non-zero coefficients in momentum space. We simulate the concept of CS on a Cu(111) surface and further reduce the measurement time by solving an open traveling sales problem for the STM tip. For further information see: https://arxiv.org/abs/1908.01903



Zero-Dimensional Exciton-Polariton Condensate in a Tunable Gaussian-Shaped Microcavity at Ambient Conditions

Fabio Scafirimuto et al., IBM Research – Zurich

Exciton-polaritons are quasi-particles arising from strong light-matter coupling in optical microcavities. Their bosonic nature allows them to create a macroscopic coherent quantum state, similar to a Bose-Einstein condensate. The condensate's properties, combined with the full optical control and the flexibility offered by the optical microcavity system, make them an optimal platform for realizing quantum analog simulators. In this work, we demonstrate room temperature exciton-polariton condensation in a 0D Gaussian-shaped defect cavity with a ladder-type polymer (MeLPPP). Our result represents a fundamental step forward towards the realization of room temperature polariton simulators.



Report on the Joint Annual Meeting 2019 in Zürich

This year, the Joint Annual Meeting of the Swiss and Austrian Physical Societies took place at the University of Zürich, on the Irchel Campus, which was a prime venue for the conference, the plenary and public talks as well as the specialized sessions. This year's edition included the participation of NCCR QSIT (Quantum Science and Technology), NCCR MaNEP (Materials with Novel Electronic Properties) and the Swiss Neutron Science Society (SGN/SSSN) which resulted in a well-attended conference. This type of conference, easily accessible locally, offers an excellent opportunity to monitor progress across the many fields of physics and is therefore a very attractive complement to more specialized meetings. It involves contributions from established and younger physicists, often offering young doctoral students the opportunity to give their first presentation. This year, the SPS also put a particular emphasis on recognizing the successful participation of Swiss high school students, gymnasium, bachelor and master students in international physics olympiads or tournaments by inviting them to participate in a special event for this next generation of potential scientists.

The Vice-Dean of UZH, Stephan Neuhauss opened the conference welcoming everyone.

Sunrise on the Irchel Campus

The program consisted this year of 9 plenary talks, 1 public lecture, 11 topical sessions and a symposium. 354 contributions had been scheduled, 247 of them talks and 107 posters. The conference gathered nearly 500 participants, the Swiss participation amounted to ~ 73 %, the Austrian one to ~ 21%, the rest came from other countries.

A major focus was this year laid on the field of quantum science and quantum computing. First, on Monday, even before the official opening of the conference, two workshops on "Machine Learning for Experimental Quantum Physics" and on programming of quantum computers took place (see editorial). Second, a public evening lecture given by Rainer Blatt on "The quantum way of doing computations" intro-

This year's plenary speakers: Claudia Draxl, Ravit Helled, Rainer Blatt, Heike Riel, ...

duced the field to a wider audience. The core event was the QSIT session with 32 contributions, complemented by a session focussing on job opportunities in emergent industries in the realm of quantum and artificial intelligence.

The General Assembly was the occasion to present numbers and statistics on the society. This year no new members have been elected for the SPS committee and only a few had to be confirmed for another term.

On Thursday evening, the conference dinner gathered more than 160 participants in the "Zunfthaus zur Meisen" in the heart of Zürich's old town, along the Limmat river. The house belongs to the winemaker's guild. This event brought the participants together in a neighborhood of densely populated historic houses and well-preserved architectural jewels. The ceilings were richly decorated, with a pre-romantic flavor, an excerpt – see photo - showing a small committee of angels sorting out the best posters, as it also is a long-standing tradition at our annual meeting. On the opposite side, another group of angels are lifting their glasses, which brings us closer to the good mood of this conference dinner evening.

The conference ended with a public symposium, prepared jointly with SCNAT, celebrating 150 years of the Mendeleev's periodic table of elements and explaining their origin - the nucleosynthesis - by the Big-Bang, burning and exploding stars.

Reports on a selection of sessions and events follow below.

Antoine Pochelon and Lukas Gallmann

The "Lichthof" was the optimal location for good interaction between exhibitors and participants during the coffee breaks and poster session.

NCCR QSIT Scientific Quantum Session

This year's NCCR QSIT scientific quantum session showcased the strength of the two quantum communities both in Austria and in Switzerland. The session was kicked off by NCCR Director Klaus Ensslin who mentioned that the two countries don't just share strong quantum science communities but also one of the forefathers of quantum mechanics: The Austrian physicist Erwin Schrödinger developed the Schrödinger Equation in 1925 during a holiday in Arosa, away from his duties as a professor in Zürich.

The talks during the quantum sessions were split between excellent speakers from both countries. They presented a broad palette of inspiring presentations from the fields of quantum computing, quantum communication, quantum simulation, quantum sensing, quantum metrology and quan-

... Olaf Reimer, Patrick Maletinsky, Monika Ritsch-Marte, Edda Gschwendtner, ...

tum engineering. A clear highlight to be mentioned were the two poster sessions at the focal point of the conference venue, with many enthusiastic young quantum scientists busy explaining their results to the crowd in front of their posters.

Andreas Fuhrer and Thilo Stöferle

Quantum and Artificial Intelligence – New Jobs for Physicists in Emerging Industries

Quantum technologies and artificial intelligence (AI) are two very hot fields with a steep rise of investment and an expanding gap in the available skilled workforce. In order to highlight opportunities for physicists in these fields, the SPS and ÖPG "Physics in Industry" sections chose AI and Quantum as focal topics for their session this year. The invited speakers vividly portrayed to the large audience the whole available gamut, ranging from young, small start-ups over established tool-providing companies to the "who-is-who" of IT technology.

Max Hettrich from *Alpine Quantum Technologies* started the session by introducing the fundamentals of quantum computing and showcased the variety of technologies that need to be tackled in their startup over the next years in order to build a rack-integrated scalable quantum computer with trapped ions.

Switching to AI, Luuk van Dijk, CEO of the Zurich-based startup *Daedalean* (26 people and a dog), explained how they want to enable autonomous flight by solving the pivotal challenge of navigation in dense air traffic once drones and personal air vehicles become ubiquitous. Amongst other qualities, physicists are needed for this job "because they like hard problems" and according to Luuk have the right mixture of theory and pragmatism.

Damian Steiger from *Microsoft* provided a glimpse into the power of quantum computing by showing how quantum-inspired algorithms can optimize traffic routing and improve the speed of magnetic resonance scan in hospitals.

Michele Dolfi from *IBM* discussed how AI systems can automatically ingest vast amounts of scientific literature and patents in order to provide e.g. material scientists with a tool that can support them in getting new insights and making discoveries.

... Anna Fontcuberta i Morral, Greta R. Patzke.

Approaching a similar target from the quantum side of things, Jan Reiner from the start-up *HQS Quantum Simulations* presented their software framework for quantum simulation of molecules and chemical reactions aimed at e.g. calculating material properties for pharmaceutical and chemical companies.

How machine learning is becoming pervasive in many established sectors of industrial production and maintenance was shown by Herwig Schreiner from *Siemens*. He gave application examples from cyber physical production systems with human/robot co-working environments to automated electrical power grid inspection.

According to Gabriel Puebla from *QZabre*, the joy of building a useful product and taking responsibility are key drivers and differentiators from academia when deciding to launch a start-up. Such entrepreneurial skills and a lot of optics, microwave and microfabrication know-how were necessary to succeed in building their "quantum microscope" prototype using scanning probe tips with nitrogen-vacancy centers.

Jan Benhelm gave insight how company strategy and product palette of *Zurich Instruments* has continuously evolved from their initial "minimum viable product" of a digital lock-in amplifier to sophisticated quantum computing control systems. As about 1/3 of their workforce are physicists with many of them in technical sales, he also told his personal journey from being an experimental ion trapper to becoming chief marketing officer.

The "Zunfthaus zur Meisen" offered an exquisite ambiente. The apéro took place in the "Saal Piano Nobile", and the dinner in the "Grosser Zunftsaal".

A beautiful view on the "Grossmünster", out of the window during the conference dinner.

David Reeb joined the AI research division at *Bosch* after 8 years with several postdoc positions in quantum information theory, now developing there the foundations to provide safety guarantees for machine learning models.

Stephan Ritter from *Toptica* illustrated how the company keeps pushing the limits of quantum optics instrumentation by participating as partner in a variety of research projects including the Quantum Flagship.

Frank Ruess gave an excellent example that careers do not always have to be streamlined right from the beginning, and turns are always possible. After a long postdoc period in experimental quantum solid state physics and a short stint at Boston Consulting Group, Frank Ruess is now project manager at *Google*.

The two presidents, Gottfried Strasser (ÖPG) and Hans Peter Beck (SPS), giving their "After Dinner Speech".

The selection of speakers and the variety of fields, seniority and career paths they presented impressively conveyed the enormous thrust that currently propels the ecosystems around quantum technology and AI forward. The speakers highlighted that there are many fascinating career opportunities for physicists in these emergent industries.

Thilo Stöferle and Andreas Fuhrer

Applied Physics & Plasma Physics; Earth, Atmosphere and Environmental Physics; combined session

This section hosted 8 speakers and 2 poster presentations and was extremely broad in its coverage.

Cazabone and Baillod presented two separate posters on the effect of density fluctuations on RF propagation in thermonuclear plasma and the effect of toroidal currents on 3-D equilibria in magnetically confined plasma respectively. Both subjects are on the frontier of fusion research and should lead to significant improvements in, on the one hand, efficiency of plasma heating using mm-waves while, on the other, stability of certain magnetic confinement concepts.

Still on the hot plasma, 3 talks were given. Van Mulders described the use of an ultra-fast suite of algorithms for the predictive modelling of tokamak plasmas: RAPTOR. This set of codes has already been used with great success on tokamaks. Tema-Biwole described the concepts using a vertical line of sight for an electron cyclotron emission diagnostic for the characterisation of non-thermal electron distributions in tokamak plasmas. This topic is of interest to ITER; the next step in magnetic confinement fusion. Finally, Offeddu, described a gas puff imaging diagnostic and its application to the measurement of fluctuations and instabilities in the edge of tokamak plasmas. It will be interesting to see if there will be synergy between the work of Cazabone and Offedu as both subjects deal with edge plasma instability.

Reducing temperature by 10 orders of magnitude Oswald described LASER cooling of C_2^-. The eventual goal of this work is to sympathetically cool anti-protons to sufficiently low temperatures to allow measurement of gravity effects on anti-matter: experiments that might shed light on a possible quantum theory of gravity. The choice of anionic molecule was described and the techniques for cooling it were described in detail along with stability analysis of traps required for cooling.

Two speakers from the University of Neuchâtel, Fischer and Drs, described novel methods for generating high power tera-hertz radiation and its applications. Fischer described the use of mode-locked femtosecond thin disk lasers for the generation of THz radiation; traditionally a part of the EM spectrum devoid of reliable sources. He described techniques and technology required to produce pulsed THz sources with repetition rates in the MHz range and, very interestingly, the generation of high harmonic radiation and comb-like sources of frequency. Drs used the thin disk source described by Fischer to generate, specifically, THz radiation. He described a 'simple' system capable of generating 300 μW up to 5 THz without external amplification. They expect to be able to scale the power to 1.3 mW with a 4 THz bandwidth.

Schneider spoke of modelling the behaviour of interacting, mobile populations of highly educated, moderately educated and poorly educated. He demonstrated an oscillatory behaviour of the relative numbers of each group depending on the initial conditions and mobility of the populations. The main conclusion was that some mobility of people of a certain group was necessary for a healthy society but not too much. The talk was followed by an interesting discussion of how the model can be improved by including transfer between groups, differential mobility between groups amongst other things.

Raemy addressed the very topical subject of forest fires and the burning of cellulose in relation to the spread and containment of forest fires. A detailed description of the experimental apparatus and a presentation of several of the main characteristics of cellulose, relative to its burning, were presented. The main conclusions were the necessity for storing water in regions at risk and the necessity for airborne fighting.

This session was a very broad and interesting session that deserved a bigger audience: folk were understandably very interested in the origin of the elements and the periodic table parallel session.

Laurie Porte

TASK

This year, the "Teilchen-, Astro- und Kernphysik" (TASK) session was organized jointly with the corresponding section of the Austrian Physical Society and in collaboration with CHIPP, the Swiss Institute for Particle Physics. The scientific program of the TASK session consisted of 56 talks and 16 posters covering a variety of fields that were organised in four topical sessions on precision physics at low energy, on high energy physics, on dark matter and neutrino physics, and last not least on detector developments. The many presentations spanned over a wide range of topics from presenting new developments in detector and accelerator technologies for current and future projects to discussing the latest physics results and their impact on theoretical predictions. The CHIPP prize for the best PhD thesis work in particle physics was given to Michał Rawlik for "his outstanding contribution to the improvement of experimental techniques aimed at detecting the Electric Dipole Moment of the neutron, and exploiting the consequences of such measurements in setting bounds on possible Axion fields". All slides presented at the TASK sessions are available from the conference page under https://indico.cern.ch/event/801048/timetable/.

The CHIPP award has been given during the award ceremony to Michał Rawlik (left: CHIPP representative Gino Isidori).

Andreas Schopper

Biophysics and Medical Physics

The Biophysics and Medical Physics session was held on Wednesday August 28 with 7 contributed talks, complemented with a plenary talk on Thursday August 29.
The plenary lecture was held by Monika Ritsch-Marte from the Medical University in Innsbruck, Austria. Prof. Ritsch-Marte has made an exciting presentation by showing us, using examples from her own research, how optical space modulators can be put to use for advanced medical-biological imaging. Notably how wave-front shaping can be achieved with the modulators or how multiplexing can benefit imaging also in dense media where light scattering becomes a major issue.
The shorty talks covered as usual a large spectrum of topics, but all related to biophysics or medical imaging. Imaging was one of the topics, and in the session, we could learn about how amyloids (proteins responsible for approximately 50 neurodegenerative diseases) are investigated by local probe microscopy. Atomic Force Microscope as well as theoretical investigations were presented. Novel investigation techniques were also among the topics, to be cited are the combination of optical and acoustic trapping for tomography or photothermal induced resonance for spectroscopy of protein in the visible range. More on the theoretical side were two talks about the properties of electrons in liquids or the phase behavior of microgel suspensions.

Giovanni Dietler

Theoretical Physics

This year it has been decided to include the theoretical talks directly in the corresponding topical session. This way, the sessions benefitted from a broad range of experimental, phenomenological, and theoretical advancements relevant in the specific topical field. This change has been perceived in a positive way and it shall be continued also in the following years.
Nonetheless, we might envisage to organize a theoretical session in future annual meetings but devoted to a specific topic. We are happy to get suggestions on possible topics for the next SPG meeting.

Philippe Jetzer

Heinz Gäggeler, Friedrich-Karl Thielemann (top) and Georges Meynet (bottom) during the symposium.

Special Session on 150 years Periodic Table

In 2019, scientists celebrate the 150th anniversary of the periodic table of chemical elements. The reason is that, in 1869, Dimitry Mendeleev for the first time arranged the elements known at that time in a table that eventually turned into the periodic table, as it is known today. The annual meeting thus finished with a symposium about this pioneering achievement. The symposium was jointly organized by the SPS and the SCNAT platform MAP and was open to the public.

The first speaker, Prof. Heinz Gäggeler from the University of Bern and the Paul Scherrer Institute, started from Mendeleev's work and its historical context. At that time, only about 60 elements were known. Mendeleev most importantly predicted the existence of additional elements, which were subsequently discovered. Gäggeler traced the history of the related discoveries, e.g. of the radioactive elements. While the discoveries of new elements were due to chemists until element no. 101, physicists took over after this. But the exploration of the chemical properties of elements is still done by chemists. Here, Gäggeler drew on his own work, e.g. on the characterization of Copernicium. Only a few atoms were available to probe the chemical features of this element!

The second speaker, Prof. Georges Meynet from the University of Geneva turned to the production of elements outside the lab. As he pointed out, the 20th century witnessed a fierce controversy on the question of whether the elements were produced in the early Universe or in stars. Today, it is agreed that we need both "pots" to form the elements. One reason is that the relative mass abundance of helium of about 25% cannot be explained on the basis of stellar physics alone, while it can be predicted by Big Bang Nucleosynthesis. While most predictions of the latter agree with the observed abundances, there is still a puzzle about the Lithium abundance.

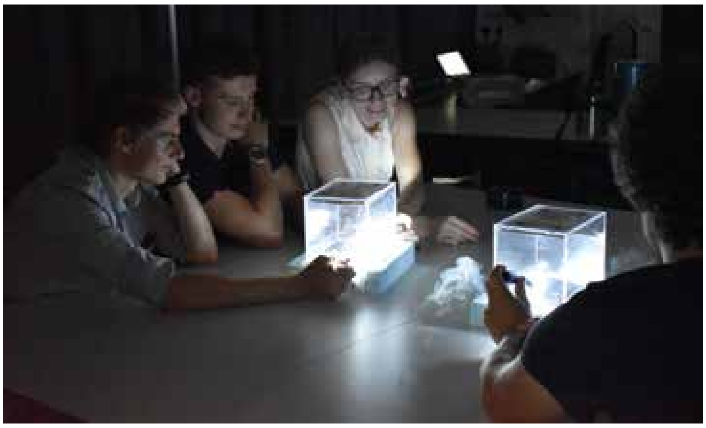
While Meynet focused on the production of fairly light elements, Prof. Friedrich-Karl Thielemann (Uni Basel) turned to the production of heavy elements, which only takes place in stars. At the microscopic level, most relevant processes are neutron capture, which may be slow or rapid, and beta decay. Whether such processes can take place depends on the availability of neutrons and the temperature. The challenge for nuclear astrophysics then is to identify settings in which the processes needed to produce certain heavy elements can be realized. For some processes, special types of supernovae or neutron star mergers may be needed.

Claus Beisbart

Nachwuchstag, Journée de la Relève

For the first time organized on this scale, the SPS invited young participants of international physics tournaments and Olympiads for a day at our Annual Meeting, with the aim of giving them a taste of physics meetings and linking them to laboratory research. The SPS is thus showing, with the support of SCNAT, its interest in excellence in training by supporting young people. The offer of such stimulating experiences for the young people is wide ranging, with either *individual competitions* (Olympiads, Schweizer Jugend forscht) at highschool level, or *group competitions* in the

Cloud chamber preparation by the participants…



…and successful observation of cosmic rays.

form of physics tournaments (highschool and university level) and naturalists' tournaments for the younger age, 12-16 (see *SPG Mitteilungen* Nr. 58, p. 51-57).

It was more than twenty young people that responded to the invitation, in fact practically everyone present at this time in Switzerland came. In the morning Award session, they were given a diploma for their participation in the international events and to honor their result. Some have notably brought back nice results from international competitions, like the young physicists' tournament team who won a gold medal this year or the young naturalist team who won the tournament 2018, to name only these.

After a common lunch in the mensa, Katharina Müller led them to a visit of the Physics Department of UZH and invited the group to a very attractive program of hands-on experiments, laboratory visits and physics auditorium demonstration. She presented the Physics Department of UZH, recalling some illustrious professors having worked here, like e.g. Rudolf Clausius, Albert Einstein or Erwin Schrödinger, and more recently Verena Meyer, first and only woman to be rector of a Swiss university at this time.

Dark matter suggested many questions on its detection.

Auditorium demonstrations, or how to stimulate experimentation

The participants then operated a cloud chamber with liquid nitrogen and alcohol vapor and observed traces of cosmic rays (photos). The laboratory visits, highly interesting, brought them to hear about gravitational waves, the building of machine learning electrical circuits, detectors to track the mysterious dark matter and biophysics. The questions the young students were asking were tantalizing. To finish the day, Peter Robmann made very clever physics demonstrations: remarkable was the fact that he did not explain the physics: he rather pointed to the changes in response when changing the input stimulation, thus rather pointing to the experimental way of doing than to knowledge… "all that you will learn if you start physics courses", were his concluding words. A very nice way of further stimulating the curiosity of an already very receptive audience.

The very positive reactions of the young people, highly appreciating this contact with research and laboratories, clearly indicates that it is an offer to further develop for these young and interested talents.

Katharina Müller and Antoine Pochelon

Aussteller Apéro der SPG an der Jahrestagung

Die Bedeutung einer physikalischen Jahrestagung widerspiegelt sich auch in der Anzahl von Firmenvertretern, die den Tagungsteilnehmern an Informationsständen ihre neuesten Instrumente, Softwarepakete und Verlagspublikationen präsentieren. Die SPG Jahrestagungen finden erfreulicherweise seit vielen Jahren das Interesse namhafter Firmen aus dem In- und Ausland, sowohl Stammkunden als auch Neuzugänge, die nicht nur mit Informationen über ihre neuesten Produkte aus erster Hand aufwarten, sondern auch Trends in der aktuellen Forschung aufmerksam registrieren. In Gesprächen mit SPG Experten wird daher oft nach der Möglichkeit einer technischen Umsetzung laufender Forschungsaktivitäten gefragt. Für die SPG sind die Kontakte zu den Firmenvertretern wertvoll, um Meinungen und Anliegen aus der Welt der Forschung in die Welt der Industrie zu bringen.

Die Intensivierung der Kontaktpflege bewog vor Jahren den damaligen SPG Vorstand um Andreas Schopper, einen speziellen Aussteller Apéro zu organisieren, um den Repräsentanten einerseits für ihr Kommen zu danken und um sie andererseits auf Technologieaktivitäten wie zum Beispiel damals bei CERN aufmerksam zu machen, die eine baldige technische Umsetzung erkennen liessen.

Dieses Jahr wurde die Idee des Aussteller Apéros erneut aufgegriffen. SPG Präsident Hans Peter Beck begrüsste die etwa fünfundzwanzig Teilnehmer, verwies auf den für beide Seiten wichtigen Informationsaustausch und stellte die anwesenden Vorstandsmitglieder vor, unter anderem von den SPG Sektionen ‚Angewandte Physik' und ‚Physik in der Industrie', sowie den ebenfalls interessierten ÖPG Präsidenten Gottfried Strasser.

Anschliessend nahm SPG Vizepräsident und SATW-WBR Mitglied Bernhard Braunecker Bezug auf den *Technology Outlook Report* TOR 2019 der Schweizerischen Akademie der Technischen Wissenschaften SATW, den sie im Auftrag des Staatssekretariats für Bildung, Forschung und Innovation SBFI alle zwei Jahre verfasst. Darin werden diesmal siebenunddreissig Technologien detailliert beschrieben und hinsichtlich ihrer Bedeutung für den Innovationsplatz Schweiz zum ersten Mal quantitativ bewertet. So sind auch die aktuellen Physikforschungsgebiete der Photonik, der Quantentechnologie, der Funktionellen Materialien und der physikalischen Modellierung von Industrieprozessen bereits im TOR 2019 aufgenommen und entsprechend ihrer aktuellen industriellen Relevanz eingeordnet.

Jeder der Anwesenden bekam ein Exemplar der *SPG Mitteilungen* Nr. 58, wo auf Seite 49 die Ergebnisse des TORs aus Sicht der Physik beschrieben werden, sowie den TOR selbst.

Die Informationsveranstaltung stiess auf erfreulich grosse Zustimmung bei den Industrievertretern und führte zu angeregten Diskussionen hinsichtlich möglicher Applikationsfelder. Es ist zu erwarten, dass die gewonnenen Erkenntnisse innerhalb der Netzwerke der Aussteller weitergegeben werden. Dank der Initiative von Katharina Müller von der Uni Zürich konnten die Aussteller am nächsten Tag noch die Physiklabors besuchen und so mit eigenen Augen sehen, wie ihre Geräte und Programme in komplizierten Experimenten zum Einsatz gelangen.

Bernhard Braunecker

The Nobel Prize in Physics 2019

The Nobel prize in Physics 2019 is awarded to cosmology and also goes to two of our Swiss colleagues. Our society congratulates all three winners warmly on this high award. Below you will find the official text of the Royal Swedish Academy of Sciences. In the next issue of the *SPG Mitteilungen* we will report in more detail about the physics.

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2019 "*for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos*" with one half to **James Peebles** (Princeton University, USA) "*for theoretical discoveries in physical cosmology*" and the other half jointly to **Michel Mayor** (University of Geneva, Switzerland) and **Didier Queloz** (University of Geneva, Switzerland; University of Cambridge, UK) "*for the discovery of an exoplanet orbiting a solar-type star*"

New perspectives on our place in the universe

This year's Nobel Prize in Physics rewards new understanding of the universe's structure and history, and the first discovery of a planet orbiting a solar-type star outside our solar system.
James Peebles' insights into physical cosmology have enriched the entire field of research and laid a foundation for the transformation of cosmology over the last fifty years, from speculation to science. His theoretical frame-work, developed since the mid-1960s, is the basis of our contemporary ideas about the universe.
The Big Bang model describes the universe from its very first moments, almost 14 billion years ago, when it was extremely hot and dense. Since then, the universe has been expanding, becoming larger and colder. Barely 400,000 years after the Big Bang, the universe became transparent and light rays were able to travel through space. Even today, this ancient radiation is all around us and, coded into it, many of the universe's secrets are hiding. Using his theoretical tools and calculations, James Peebles was able to interpret these traces from the infancy of the universe and discover new physical processes.
The results showed us a universe in which just five per cent of its content is known, the matter which constitutes stars, planets, trees – and us. The rest, 95 per cent, is unknown dark matter and dark energy. This is a mystery and a challenge to modern physics.
In October 1995, Michel Mayor and Didier Queloz announced the first discovery of a planet outside our solar system, an exoplanet, orbiting a solar-type star in our home galaxy, the Milky Way. At the Haute-Provence Observatory in southern France, using custom-made instruments, they were able to see planet 51 Pegasi b, a gaseous ball comparable with the solar system's biggest gas giant, Jupiter.
This discovery started a revolution in astronomy and over 4,000 exoplanets have since been found in the Milky Way. Strange new worlds are still being discovered, with an incredible wealth of sizes, forms and orbits. They challenge our preconceived ideas about planetary systems and are forcing scientists to revise their theories of the physical processes behind the origins of planets. With numerous projects planned to start searching for exo-planets, we may eventually find an answer to the eternal question of whether other life is out there.

This year's Laureates have transformed our ideas about the cosmos. While James Peebles' theoretical discoveries contributed to our understanding of how the universe evolved after the Big Bang, Michel Mayor and Didier Queloz explored our cosmic neighbourhoods on the hunt for unknown planets. Their discoveries have forever changed our conceptions of the world.

Plenary Talks

Meanwhile a well accepted service for our members: after the annual meeting we ask the speakers of the plenary talks to summarize their presentation as an extended abstract. You will find the articles from those speakers willing to contribute below, they are later also collected as an own series on our webpage (https://www.sps.ch/en/articles/plenary-talks/).

Understanding Giant Planets

PT 1/2019

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Center for Theoretical Astrophysics & Cosmology, University of Zürich, CH-8057 Zürich

Planets are mysterious astronomical objects that are still being investigated. Giant planets are key planets to explore because they have a critical role in shaping the architecture of young planetary systems. This is due to their fast formation (they have to form early enough to accrete hydrogen-helium (H-He) gas), and their large gravity that influence the dynamical properties of asteroids and comets, which can lead to delivery of volatile elements (e.g., water) to the inner planetary system. In addition, the composition of gas giant planets provides information on the physical and chemical properties of proto-planetary disks, the birth places of planets.

Jupiter is a gas giant planet, and is the most massive planet in the Solar System. Jupiter's mass is about 318 times the mass of the Earth, and its average radius is more than ten times the Earth's radius. Jupiter is mostly made of H-He, and this is the reason it is known as a "gas giant planet". However, the interior of the planet is not in the gaseous phase due to the high pressures. Therefore, one should think of giant planets as being "fluid" and not "gaseous".
Jupiter also consists of heavier elements, such as oxygen, carbon and silicon (in astrophysics heavy elements refer to all the elements heavier than helium) but the total mass of these heavy elements in the planet is unknown.

It is also unclear whether Jupiter has a heavy-element (rocks, ices) core in its center. While the mass of the core is unlikely to be more than ten times the mass of the Earth (and therefore only ~3% of Jupiter's mass), and the total heavy-element mass is expected to be only a small fraction of its total mass (~10%), the heavier elements play a critical role in understanding the formation process of giant planets, which is a long-lasting challenge in planetary science.

In the standard model for giant planet formation, also known as core accretion, a giant planet is formed in three main stages:

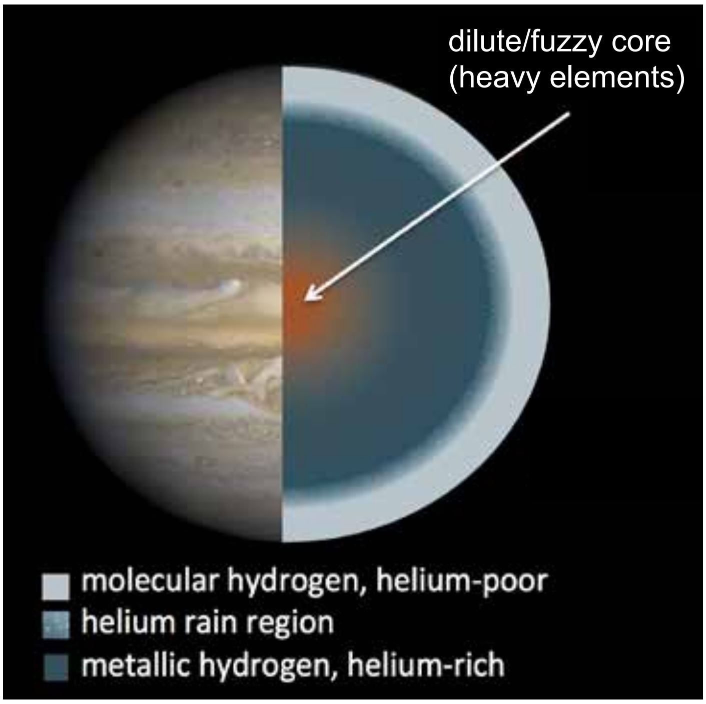
(1) Core/heavy-element accretion: core formation by accretion of planetesimals (primordial "asteroids" made of rock and ice) until the planet empties its gravitational dominating region (known as feeding zone). At this stage, the growing planet is primarily composed of heavy elements with a negligible fraction of a H-He envelope.

(2) Slow envelope accretion: the heavy-element accretion rate decreases, and the H-He accretion rate increases until the envelope accretion rate exceeds the heavy-element accretion rate.

(3) Runaway gas accretion: once the H-He mass is comparable to the heavy-element mass, a rapid hydrodynamic accretion of H-He initiates, and a gas giant planet is formed.

In this formation picture, one expects the giant planet have a distinct heavy-element core and a gaseous H-He envelope. Indeed, giant planet formation simulations originally assumed that the accreted planetesimals (i.e., heavy elements) go to the center of the planet and form a core. As a result, giant planets were thought to have a simple core+envelope internal structure, with a relatively massive core.

However, recent giant planet formation simulations that follow the distribution of the accreted heavy elements during the planetary growth, show that once the core reaches a couple Earth masses most of the accreted heavy elements dissolve and remain in the gaseous envelope. As a result, there is no clear transition between the “core” and “envelo-



A sketch of Jupiter's internal structure with a dilute core/composition gradient in the deep interior. The different colors correspond to different elements. Jupiter's envelope is typically divided into an outer envelope where hydrogen is in molecular form and an inner envelope in which hydrogen is ionized (metallic). The metallization of hydrogen in Jupiter's deep interior is responsible for the generation of its strong magnetic field.
Helium was measured to be depleted in Jupiter's atmosphere. Indeed, simulations show that helium is expected to separate from hydrogen, leading to "helium rain" which results in an increase in the helium fraction in Jupiter's inner envelope, as indicated in the sketch.

pe" and the forming giant planet has an internal structure with composition gradients. In this case, Jupiter's core can no longer be thought of as a pure heavy-element central region with a density/composition jump at the core-envelope-boundary, but as a central region that is highly enriched with heavy elements, which could be gradually distributed or homogeneously mixed. Such a fuzzy/dilute core can extend to a few tens of percents of the planet's total radius, and could also consist of lighter elements (i.e., H-He). In this updated picture of giant planet formation, there is an increase in the heavy-element fraction towards the planetary center. If the composition gradient is steep enough in the deep interior, this region can also be stable against large-scale convection.

Internal structure models of Jupiter are designed to fit the observed physical data of the planet, such as its mass, radius, gravitational and magnetic fields, atmospheric composition, and rotation. New Jupiter internal structure models that fit Jupiter's gravity field as accurately measured by the NASA Juno mission, also indicate that the planet is not homogeneously mixed, and that Jupiter can have a fuzzy/dilute core.
As discussed above, such a core is a natural result of planetesimal dissolution in the atmosphere of a growing giant planet. Therefore, for the first time, we have a link between planetary structure and planet formation models.

These recent developments have taught us that Jupiter's interior is inhomogeneous, and that there is an increase in the heavy-element mass towards the planetary center. Overall, we have learned that giant planets are not simply mixed balls of H-He, but are objects with complex internal structures that need to be studied further. This requires a good understanding of the underlying physical and chemical processes, such as the equations of state of the materials and their interactions, miscibilities, convective mixing, etc. We also have to keep in mind that in order to link planetary formation with the current-state internal structure we must simulate the planetary long-term (a few 10^9 years) evolution, and develop a unified theoretical framework for giant planet formation-evolution-interior.

The origin and internal structure of Jupiter are still being investigated. Since Jupiter is used as a giant planet prototype, the knowledge we collect is then applied to giant exoplanets, with the aim to characterize these objects, and put our Solar System in perspective.
Although many questions remain open, this is a golden era in giant planet exploration. The measurements of the ongoing Juno mission, the characterization of many giant planets around other stars, and the theoretical efforts provide new insights on the nature of gas giant planets.

Synthetic holography with spatial light modulators for biophotonics applications

PT 2/2019

Monika Ritsch-Marte, Institute for Biomedical Physics, Medical University of Innsbruck, Müllerstrasse 44, AT-6020 Innsbruck

Optical wavefront shaping with spatial light modulators (SLMs), such as deformable mirrors, digital micro-mirror devices or liquid crystal (LC) panels, has become a powerful tool in Biophotonics [1]. LC-SLMs are particularly flexible, since they contain millions of individually addressable pixels to create high-resolution phase-actuation patterns. The phase-delay introduced by a pixel is determined by the tilting angle of the birefringent liquid crystal molecules which is set by applying a voltage to the pixel. Binary LC-panels, which only have 2 phase delay values corresponding to 0 and π, can typically operate much faster (at kHz refresh rate) than the types of LC-SLMs which allow 8-bit or more in phase level depth. The latter, however, support more possible settings and have higher diffraction efficiency.

A typical application of phase-masks on an SLM is the realization of programmable gratings or Fresnel lenses, for instance to create "holographic optical tweezers" comprising of one or more steerable laser spots. Optical tweezers have become a widespread tool in biomedical research, since they allow one to capture and move microscopic objects in a liquid environment in a precise and non-invasive way. Moreover, optical traps provide a means to *quantify* mechanical forces at work in cell biology *in situ*, for instance between motor molecules and filaments. A disadvantage of optical tweezers is the fact that the achievable force range is usually limited to the pico-Newton regime, as the optical power required to go higher in force would induce considerable heating by absorption. Combining optical trapping with another static, but strong force field – such as a MHz ultrasound wave in a microfluidic chamber – one can levitate heavy particles while still profiting from the full steering capability of holographic tweezers [2], cf. Fig. 1.

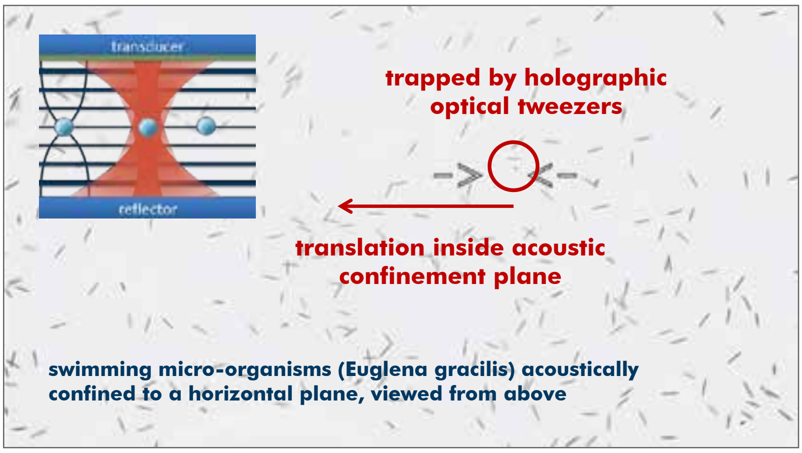


Fig. 1: Interactively steerable holographic optical tweezers created by wavefront shaping with a spatial light modulator with an ultra-large manipulation volume: In order to be able to manipulate large (length 70 μm) actively swimming micro-organisms, an auxiliary acoustic standing wave is used.

But the use of wavefront shaping is not restricted to applications in optical micromanipulation: An SLM can also be integrated into optical imaging systems, making the microscope or imaging system programmable and adaptable with respect to the needs of specific samples. In the synthetic holography approach, one *calculates* the holographic phase masks and sends them to the SLM which acts as a reconfigurable phase mask.

Placing the SLM in a Fourier plane with respect to the sample, one can emulate various microscopy techniques with the SLM acting as a programmable Fourier filter and rapidly toggle between them (cf. Fig. 2). Wavefront shaping with SLMs also enables one to reconstruct intensity patterns in the far-field or in a specified plane (cf. Fig. 3a), for example with the goal of targeting structures for optogenetic stimulation of neurons in 3D in the depth of brain tissue.

A particular strength of the synthetic holography approach is the possibility to *multiplex*, which means that one can 'pack' several tasks into one computer-generated hologram [3]. One can, for instance, record microscopic images that contain sub-images belonging to different imaging modalities, or from different depths inside the sample, or with different parameter settings.

It is even possible to read out several holograms for specific illumination colours from the same phase mask: Simultaneously incident illumination wavelengths will suffer different phase retardation from the same voltage pattern applied to the display, because of the difference in optical thickness of the LC layer and due to its colour-dispersion. The freedom of being able to add multiples of 2π without changing the effect of a diffractive optical element gives one the necessary degrees of freedom to accommodate several holograms, for instance for RGB-colour projection of a holographic image (cf. Fig. 3b). In this way, one may also incorporate optical imaging (in the visible) and optical trapping (in the near-infrared) in one and the same phase mask pattern.

Wavefront shaping with SLMs has become indispensable in many fields of applied optics, and will continue to make optical imaging and trapping programmable and adaptable with ever- increasing speed and control of detail.

[1] Maurer, C., Jesacher, A., Bernet, S. and Ritsch-Marte, M., 2011. *What spatial light modulators can do for optical microscopy*, Laser & Photonics Reviews, 5(1), pp.81-101.

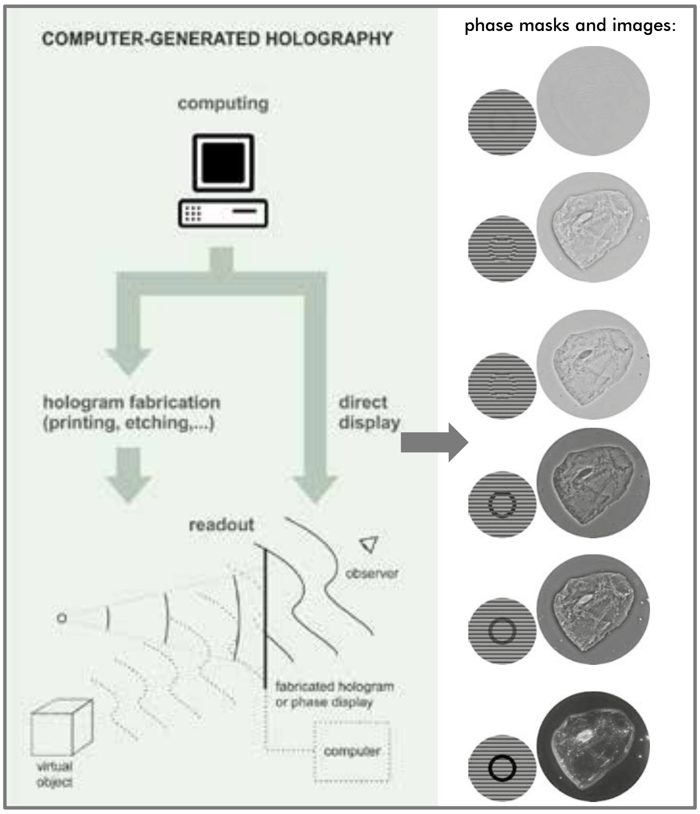


Fig. 2: In the synthetic holography approach phase patterns performing a desired task are calculated and sent to the SLM which acts as a reconfigurable phase mask. In this way, various microscopy techniques can be emulated by simply changing the phase mask, to change to a different imaging modality or to customize the parameter settings to match a given sample - without any adjustment of hardware components. In the example on the right, a thin phase object (an unstained epithelial cell) is imaged by phase masks inspired by Zernike phase contrast. The varying modulation depth of the saw-tooth grating inside the ring, as well as its relative phase shift of the gratings inside and outside the ring, influence the appearance of the image substantially. One can go from an un-contrasted bright-field image (top), to an optimized phase-contrast image, to a dark-field image (bottom) [3].

[2] Thalhammer, G., Steiger, R., Meinschad, M., Hill, M., Bernet, S. and Ritsch-Marte, M., 2011. *Combined acoustic and optical trapping*, Biomedical optics express, 2(10), pp.2859-2870.
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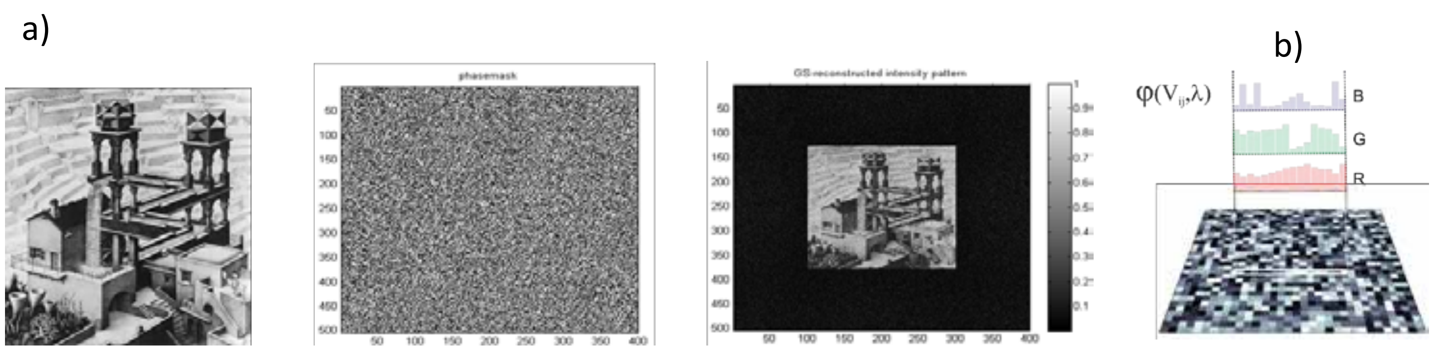

Fig. 3: Iterative algorithms are used to find a phase mask which reconstructs a desired intensity distribution in the far-field or in a specific distance from the phase mask. Fig. a) shows the image to be reconstructed (left), the phase mask calculated by a Gerchberg-Saxton search algorithm (middle) and the simulated reconstruction in the far-field (right). b) A given voltage pattern applied to the SLM panel is read out differently by different wavelengths, due to differences in the optical path length as well as colour dispersion in the LC layer. This may be utilized to multiplex several holograms into one pattern, e.g. for multi-colour holographic image reconstruction, or for combined optical trapping (by a near-infrared laser beam) with SLM-augmented imaging (in the visible).

First Electron Acceleration in AWAKE

Edda Gschwendtner, CERN, on behalf of the AWAKE Collaboration

The potential of reaching high accelerating gradients up to three orders of magnitude stronger than conventional methods has been successfully demonstrated with plasma wakefield acceleration in the last decades; electrons were accelerated to energies up to ~8 GeV using short, PW laser pulses to drive wakefields in 20 cm long plasma cell [1]. Using a short high-charge electron bunch driver an energy gain of 42 GeV in 85 cm, corresponding to 52 GV/m accelerating gradient has been achieved [2].

However, the energy carried by a laser or electron drive beam is only at the order of ~10s Joules limiting the maximum energy gain of electrons accelerated in a single stage. In order to accelerate electrons to TeV energies (equivalent to 2 kJ in 2×10^{11} electrons) several stages are required in both laser- and electron driver beam experiments.

Proton drive beams available today carry much higher energies (typically 10s to 100s of kJ) and could therefore accelerate electrons to the energy frontier in a single plasma stage, simplifying and shortening the accelerator.

The maximum field of plasma wake scales with the plasma electron density; at least 10^{14} cm^{-3} are required to reach accelerating gradients of GV/m and above. Typically, large amplitude wakefields are produced by short bunches at the order of the plasma wavelength and at these densities the plasma wavelength is of the order of a millimeter or smaller. However, proton beams today are 3 – 12 cm.

Long proton bunches can nevertheless drive strong wakefields taking advantage of the self-modulation [3] of the proton bunch; the process of seeded self-modulation starts from a seeding wakefield in the plasma whose transverse field acts on the proton beam and modulates its radius. The wakefield's amplitude grows exponentially from head to tail of the bunch and along the propagation distance. At saturation, the initially long and smooth beam is split into a train of micro-bunches near the axis, with periodicity equal to the electron plasma frequency. The micro-bunches resonantly excite a strong plasma wave.

The ***A****dvanced* ***WAKE****field* Experiment, AWAKE, is a proton driven plasma wakefield acceleration experiment and was approved in 2013. In 2016/17 AWAKE observed the strong modulation of high-energy proton bunches in a 10 m long plasma; the results represent the first ever demonstration of strong plasma wakes generated by proton beams. In 2018 AWAKE demonstrated for the first time the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields [4].

Figure 1 shows a schematic drawing of the AWAKE experimental facility. A proton bunch with intensity on the order of 3×10^{11} protons, energy of 400 GeV/c (19.2 kJ) and a length of 6 - 12 cm is extracted from the CERN SPS towards the AWAKE experimental area. The bunch is focused at the entrance of the plasma to a transverse beam rms size of $\sigma_r = 0.2$ mm. The AWAKE plasma is 10 m long, has a radius

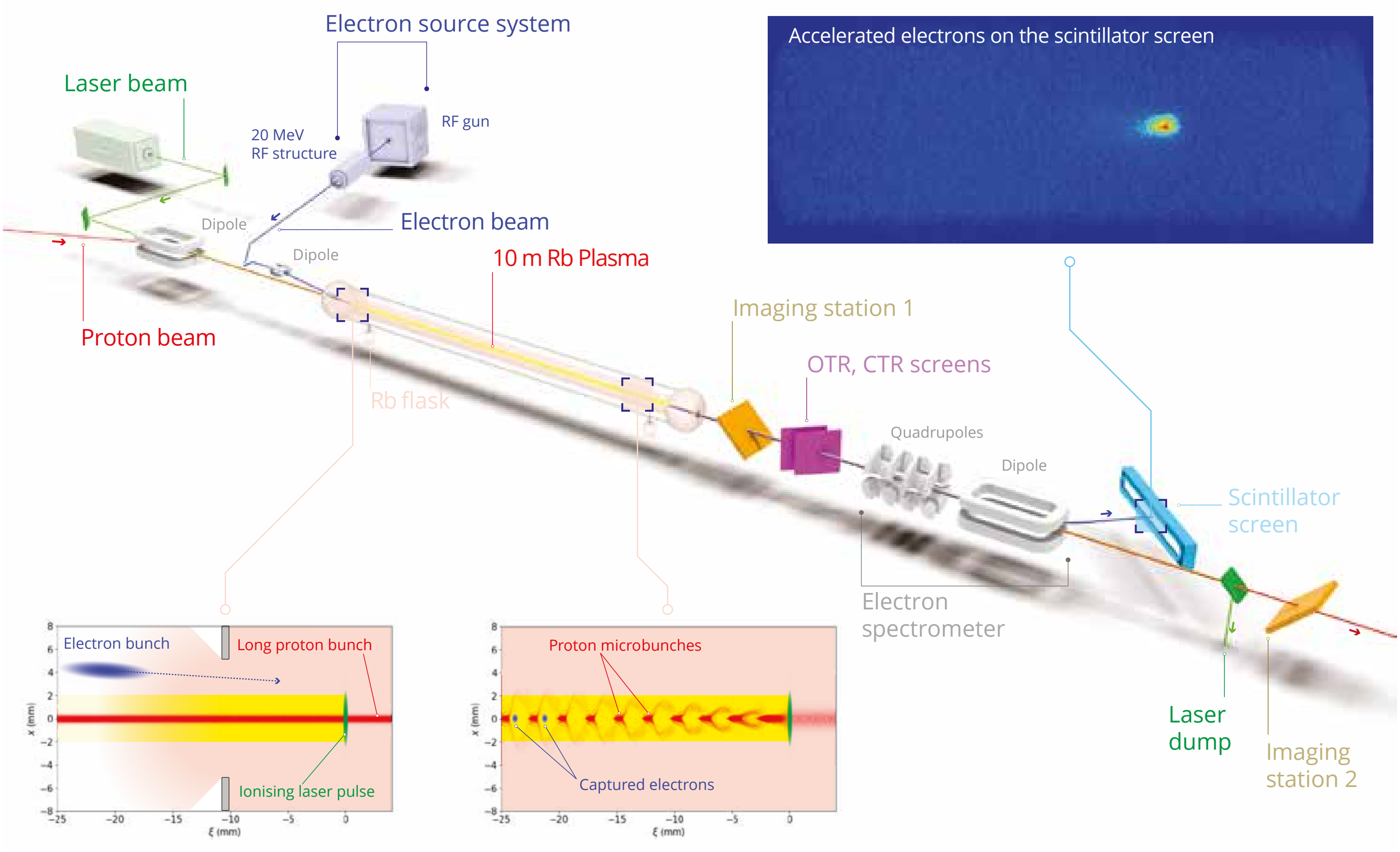

Fig. 1: Schematic layout of the AWAKE experiment.

of approximately 1 mm and density uniformity better than 0.1%.

To create the plasma a heat exchanger evaporates rubidium and a 4.5 TW laser pulse ionizes the outermost electrons of the rubidium atoms. The vapor (and therefore the plasma density) is adjustable between 0.5 – 10 × 10^{14} atoms/cm^3.

The laser (100 fs pulse length, 450 mJ energy) is overlapped in space and time with the proton beam, which allows for seeding the proton self-modulation by creating a sharp ionization front inside the proton bunch. The protons ahead of the laser pulse propagate in rubidium vapor, the ones after in the plasma self-modulate to micro-bunches, as seen in the left lower pictures of Fig. 1.

20 MeV electrons are externally injected into the plasma to probe the wakefields and demonstrate electron acceleration. The electrons are produced in an S-band photo-injector system and transported to the plasma entrance. The beam diagnostics systems and the electron spectrometer measuring the energy of the accelerated electrons on a scintillator screen (see upper right figure in Fig 1.) are installed downstream the plasma.

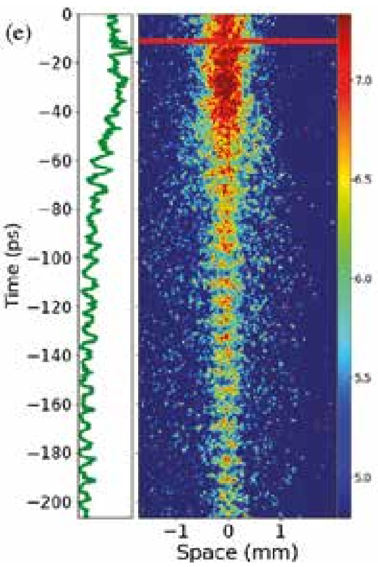

Fig. 2: Streak camera measurement of the self-modulated proton micro-bunches beam after the ionizing laser pulse (red line) and the start of the plasma

Fig 2. shows results of the streak camera measurement of the self-modulated proton micro-bunches beam after the ionizing laser pulse and the start of the plasma [5]. The micro-bunch periodicity is equal to the electron plasma period.

The measurements showed that during the self-modulation process the wakefield amplitude grows from the initial seed value according to the self-modulations growth rate until saturation both along the bunch and along the plasma [6], as also predicted by simulations. In addition by seeding the self-modulation with sufficient wakefield amplitude the process is reproducible and stable. This is particularly important since the witness electron bunch is injected several micro-bunches (usually 30-100) behind the seed point, where the controlled phase and wakefield period keeps the electrons in the accelerating and focusing phase.

Fig. 3 shows the energy of the accelerated electrons after the 10 m plasma as a function of the plasma density without and with a positive plasma density gradient (~2.2% over 10 m) [6]. The measurements demonstrated that the energy gain increases with plasma density. Electron acceleration

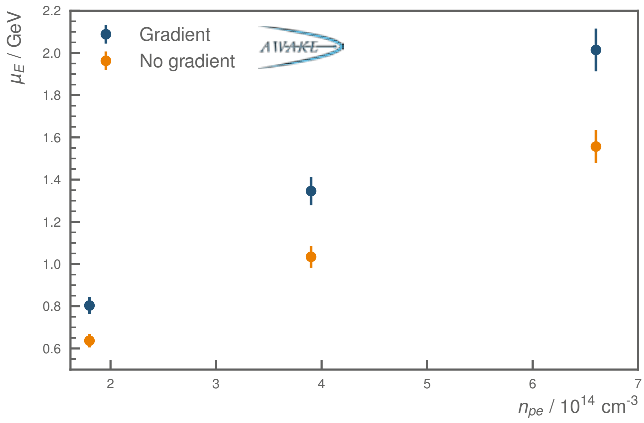

Fig. 3: Accelerated electron energy for different plasma densities with (blue) and without (orange) gradient in the plasma density.

up to 2 GeV in the plasma wakefield driven by the self-modulated proton beam has been observed.

AWAKE Run 1 was a proof-of-concept experiment [7]. The goals for AWAKE Run 2 are to bring the R&D development of proton-driven plasma wakefield acceleration to a point where particle physics applications can be proposed and realized. Therefore AWAKE Run 2 starting in 2021 after CERN Long Shutdown 2 aims to achieve high-charge bunches of electrons accelerated to high energy, about 10 GeV, while maintaining beam quality through the plasma and showing that the concept is scalable to long acceleration distance scales. In order to achieve acceleration with low energy spread and emittance preservation, the electron beam injected in the plasma needs higher energy (165 MeV) and much shorter electron bunches (~200 fs). X-band technology will be used for the new electron source system. Two plasma sources are proposed in Run 2; in the first plasma source the proton bunch self-modulates until saturation is reached. A density step will be introduced to freeze the modulation process and allow for much higher final electron energies over long acceleration distances. The electron bunch will be injected into the stable wakefields driven by the micro-bunch trains in the second plasma.

By the successful end of AWAKE Run 2 the AWAKE scheme could be used for first high-energy physics applications already in the intermediate time-scale; first high energy experiments are seizable, where proton driven plasma wakefield acceleration technology could be used for fixed target experiments for dark photon searches and also for future electron-proton or electron-ion colliders, where low luminosity is acceptable.

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Economic Materials Design for Clean Energy Applications

PT 4/2019

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The worldwide quest for clean and renewable energy resources has triggered an intense research interest in solar-driven catalysis. Given that solar light is our most reliable and inexhaustible energy source, its direct conversion into storable hydrogen fuel and oxygen through splitting of water ("artificial photosynthesis") is a highly promising strategy. Physics and chemistry meet at new synthetic and analytical frontiers of this competitive research area [1].

The most serious bottleneck of water splitting remains the water oxidation half reaction with its thermodynamically and kinetically demanding four electron transfer process. This renders the development of efficient and noble metal-free water oxidation catalysts (WOCs) an important and urgent challenge. Over the past decades, a wide range of new molecular and heterogeneous WOCs has been developed and tested with respect to their photo- and electrocatalytic activity. However, their design and optimization principles still remain empirical to a large extent, because the complex mechanisms of water splitting with different WOCs are still intensely investigated, along with their changes under the frequently harsh conditions for water oxidation. Concerning WOC design paradigms, for example, Nature's oxygen evolving complex (OEC) at the center of Photosystem II, a cuboidal $\{CaMn_4O_5\}$ complex, offers attractive inspiration for structural motifs and self-healing properties.

Our systematic approach to noble metal-free WOCs covers a wide dimensionality spectrum bridging molecules and solids, from cuboidal clusters over nanomaterials to new disordered coordination polymer catalysts. We complement these strategies with new ex situ and in situ analytical studies of WOC dynamics and their post-catalytic stability. The research spectrum is rounded off with investigations into the fundamental and largely unresolved issue aspect of WOC assembly and growth pathways in solution.

Concerning WOC synthesis strategies, we place special emphasis on cobalt-based catalysts, which offer attractive opportunities to directly compare physics-inspired design concepts with bio-inorganic approaches. In a series of case studies on pure and lithiated cobalt oxides, we underscored the key roles of high crystallinity and optimal conductivity in heterogeous WOC design [2]. These insights were applied on the electronic structure tuning of a series of $La_{1-x}Sr_xBO_3$ (B = Fe, Co, Mn, Ni) perovskite-type WOCs with increasingly metallic character upon higher extents of Sr^{2+} substitution. These conductivity-tuned perovskites were subjected to standard photocatalytic water oxidation tests in order to investigate correlations between the molecular process of O_2 evolution with gradual changes in the electronic structure of the WOCs (using $[Ru(bpy)_3]^{2+}$ as electron acceptor and peroxodisulfate as sacrificial electron acceptor, cf. Fig. 1). Indeed we obtained clear physical guidelines for perovskite WOC optimization, because a higher metallic character of the perovskite WOCs led to continuously enhanced oxygen evolution activity [3].

However, current studies of spinel-type Co_3O_4 WOCs as excellent model systems demonstrate that not only the inherent structural design, but also the preparative pathways and underlying formation mechanisms can exert a decisive influence on the WOC activity [4]. These results illustrate the fundamental challenge of predicting and controlling the complex assembly processes of functional materials in aqueous media. Additionally, they highlight paradigm changes in current catalysis research towards a dynamic concept of heterogeneous (water oxidation) catalysts, which may undergo subtle or drastic structural and compositional transformations over longer reaction times.

In contrast to the demanding monitoring of heterogeneous WOCs under operational conditions, their molecular counterparts offer more convenient spectroscopic and modeling options to address these central questions of catalyst assembly along with oxygen evolution mechanisms. In our parallel line of bio-inspired WOC development, we brought forward a series of molecular $\{Co(II)_4O_4\}$ cubane-type water oxidation catalysts. Their first representatives, namely $[Co^{II}_4(hmp)_4(\mu\text{-}OAc)_2(\mu_2\text{-}OAc)_2(H_2O)_2]$ (hmp = 2(-hydroxymethylpyridine) [5] and the $[Co^{II}_3Ln(hmp)_4(OAc)_5H_2O]$ (Ln = Ho – Yb) series [6], displayed enhanced catalytic activity due to the presence of flexible aqua and acetate ligands around the cuboidal core. We thus showed the beneficial effect of translating key motifs of the natural $\{CaMn_4O_5\}$ OEC into readily accessible molecular Co-WOCs.

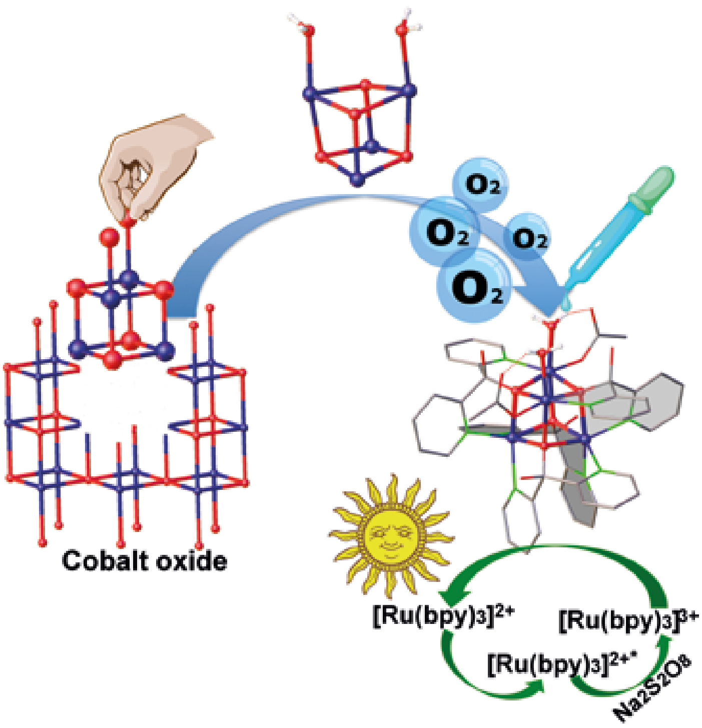

Fig. 1: $[Co_4(dpy\{OH\}O)_4(OAc)_2(H_2O)_2](ClO_4)_2$ cubane water oxidation catalyst (right) with the characteristic $\{H_2O\text{-}Co^{II}_2(O)_2\text{-}OH_2\}$ edge-site motif (top) within a cut-out of cobalt oxide (left) as a representative WOC (image modified from Song et al., 2017, https://pubs.acs.org/doi/abs/10.1021/jacs.7b07361).

We then systematically proceeded to link such molecular cobalt cubane WOCs to Co_3O_4 spinels as their heterogeneous counterparts by introducing the $[Co_4(dpy\{OH\}O)_4(OAc)_2(H_2O)_2](ClO_4)_2$ cubane with the special $\{H_2O\text{-}Co^{II}_2(O)_2\text{-}OH_2\}$ edge-site motif [7]. This motif had recently been identified as the *sine qua non* structural moiety for efficient catalytic oxygen production on heterogeneous cobalt oxide surfaces [8]. The edge-site $\{Co(II)_4O_4\}$ cubane can thus be regarded as a cut-out of cobalt oxide surfaces, and we demonstrated its molecular stability and high performance under photochemical water oxidation conditions with a wide range of analytical investigations. Comparison to a close molecular analogue with a single cobalt center demonstrated that the edge-site motif is superior in both oxide and molecular catalysts.

Furthermore, the $\{Co(II)_4O_4\}$ cubane WOCs opened up new territories in the widely unexplored assembly mechanisms of cluster-type catalysts in solution. For the first time, we obtained an entire family of molecular Co(II)-cubanes from a convenient synthetic protocol just by varying the type and amount of a plain inorganic salt additive [9]. With a combination of retrosynthetic experiments and DFT calculations, we first identified the most plausible pathways for two fundamentally different cubane types among the family. The unprecedented and strong structure-directing effect of the inorganic counteranions is currently under investigation, and its complexity sheds light on the advanced physico-chemical techniques that are now required to fully understand and control cluster assembly mechanisms in solution as well as the role of apparently innocent "spectator" anions.

Both our molecular and heterogeneous lines of (cobalt) WOC design finally converged recently in unraveling the first disordered 1D-coordination polymer catalyst, referred to as Co-dppeO_2 (dppeO_2 = 1,2-bis(diphenylphosphino) ethane dioxide) [10]. This exceptionally durable and commercially available electrocatalyst emerged from serendipitous chemical screening with a complete lack of long-range order and no evident relations to known solid materials. We unraveled its unconventional structural features with a two pillar approach based on X-ray absorption and PDF techniques, complemented by in situ FT-IR monitoring of Co-dppeO_2 formation and DFT modeling of competent intermediates. Surprisingly, we found that the high activity of disordered Co-dppeO_2 was due to self-organized formation and embedment of the $\{H_2O\text{-}Co^{II}_2(OH)_2\text{-}OH_2\}$ edge-site motif into flexible channels of the robust dppeO_2 ligands, which furthermore hosted plenty of water molecules. This innovative WOC connects essential inorganic with biological motifs and highlights the massive potential of dynamic and disordered materials to bring forward new types of resilient catalysts.

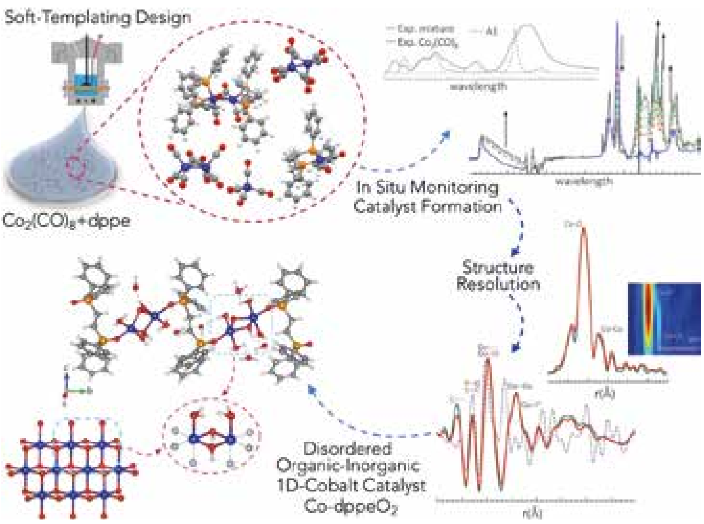

*Fig. 2: Complementary in situ FT-IR monitoring and X-ray total scattering/absorption strategies together with atomistic modeling and the results of numerous other analytical techniques revealed the innovative architecture of the disordered, high performance water oxidation catalyst Co-dppeO_2. (modified from Triana et al., Matter **2019**, DOI: 10.1016/j.matt.2019.06.021)*

Despite continuous synthetic progress, the comprehensive analysis of all WOC stages – from their formation over operational mechanisms to deactivation and decay – is still far from routine. To this end, pushing the boundaries of analytical techniques offers exciting collaborations between physics and chemistry. Concerning catalyst formation pathways, we showed that even binary spinel-type Co_3O_4 WOCs display complex temperature-dependent changes in their hydrothermal growth mechanisms. Taking non-oxide transition metal carbodiimide (MNCN, M = Co, Ni, Cu, Mn) catalysts as a well-defined model system, we demonstrated their operational stability with a new application of in situ XAS and in situ Raman spectroscopy on convenient screen printed electrodes [11]. We then proceeded to address their nanoscale analysis on electrode surfaces with the first application of novel XUV TOF-MS techniques to such WOCs [12]. Most recently, we used a combination of TPS and PEIS measurements to investigate the role of several $\{Co(II)_4O_4\}$ cubane WOCs as co-catalysts on hematite photoanodes. Molecular photoanodes are just beginning to be explored, and the role of co-catalysts on electrodes in general remains at the center of controversial debates. For the first time, we revealed a dynamic role of molecular and heterogeneous cobalt co-catalysts on photoanodes, proceeding from hole reservoirs to catalytic centers as a function of applied bias [13].

The future of artificial photosynthesis is bright with the power of new disordered, hybrid and dynamic catalyst types emerging on the horizon. This new generation of materials requires a new repertoire of lab-scale analytical methods that enable the rapid analysis of complex disorder as well as versatile in situ monitoring of catalysts, such as benchtop XAS systems. We look forward to exciting interdisciplinary work at the interface of advanced physical methodologies and techniques with complex chemical systems.

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Artificial intelligence in materials science - hype or revolution?

PT 5/2019

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The growth of data from simulations and experiments is expanding beyond a level that is addressable by established scientific methods. The so-called "4 *V* challenge" of Big Data – *Volume* (the amount of data), *Variety* (the heterogeneity of form and meaning of data), *Velocity* (the rate at which data may change or new data arrive), and *Veracity* (uncertainty of quality) – is clearly becoming eminent also in the sciences. Controlling our data, in turn, sets the stage for explorations and discoveries.

Novel approaches and tools of Artificial Intelligence (AI) can find patterns and correlations in data that cannot be obtained from individual calculations or experiments and not even from high-throughput studies. In fact, data-driven research is adding a new research paradigm to the scientific landscape, as indicated in Figure 1, which shows the historical development of the research paradigms in our field.

For a real breakthrough, *Open Data* and sharing, as well as an efficient data infrastructure is key. In other words, for shaping this forth paradigm and contributing to the development or discovery of improved and novel materials, data must be what is now called FAIR - Findable, Accessible, Interoperable and Reusable [2].

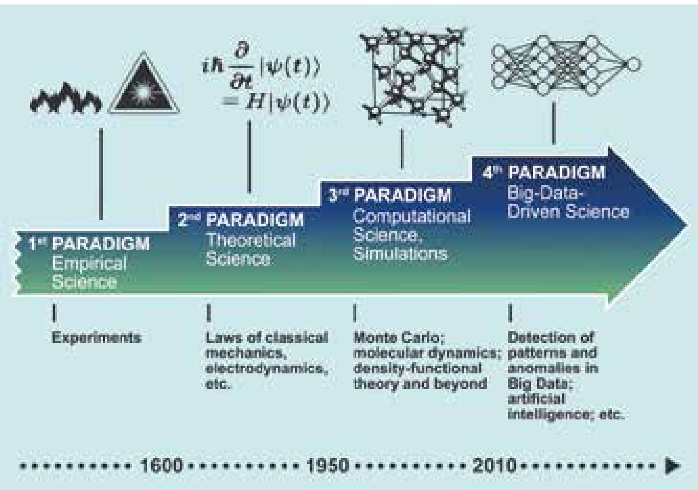

Figure 1: Development of research paradigms of materials science and engineering (from [1]).

The NOMAD Laboratory [3,4] is a living example for such infrastructure in computational materials science, comprising the NOMAD *Repository* (raw data) and its *Archive* (normalized, i.e. code-independent data). The NOMAD *Encyclopedia* is a web-based public platform that visualizes the properties of this large variety of materials. The NOMAD Analytics Toolkit provides a collection of examples and tools to demonstrate how materials data can be turned into knowledge by AI approaches (e.g. [5,6]).

What are the challenges [7] ahead of us to make the data revolution happen? On the computational side, reliable error quantification (for a very first step, see [8]) and trust levels that help making data comparable; efficient algorithms and implementations of high-level methods for creating the *right* data; and novel AI tools are among them. Figure 2 sketches this situation.

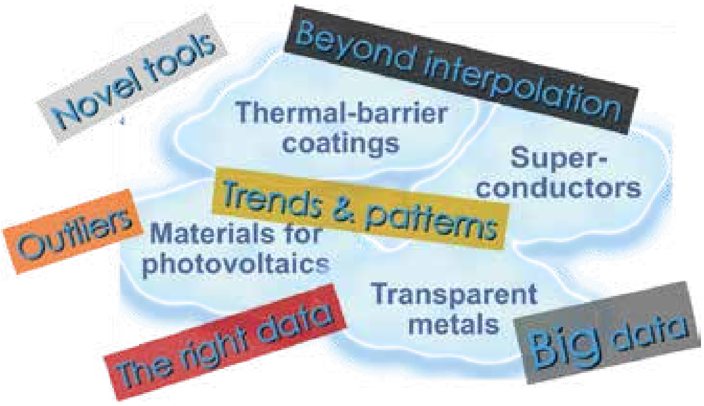

Figure 2: Challenges on the way to novel discoveries.

It also indicates NOMAD's long-term vision, namely to provide (high-dimensional) materials maps that tell where in the composition and compound space one can find materials for a certain application. The very big next step, that has indeed already been started [9], is exploring FAIRness in data of experimental materials science, synthesis, and a number of functional materials.

*Work in collaboration with Matthias Scheffler and the entire NOMAD Team.

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Nachruf Jean-Pierre Blaser

Am 29. August 2019 verstarb Jean-Pierre Blaser im Kreis seiner Familie an seinem Wohnort Schneisingen, Aargau. Mit ihm verliert die Schweiz einen Wissenschafter, der die schweizerische Physik nachhaltig geprägt hat.

Jean-Pierre Blaser 1984, anlässlich "10 Jahre 'Strahl' am SIN".

Jean-Pierre Blaser wurde am 25. Februar 1923 geboren und wuchs in Zürich auf. Nach der Matura begann er an der Universität Zürich mit dem Studium der Chemie und Mathematik. Im dritten Semester wechselte er auf Anraten von Professor Louis Kollros, der an der ETH Geometrie lehrte und wie Blasers aus La Chaux-de-Fonds stammte, an die ETH, um Physik zu studieren. Im Jahr 1948 diplomierte er bei Professor Georg Busch mit einer Arbeit in Infrarotspektroskopie. Blaser interessierte sich für Astronomie, fand aber kein Einvernehmen mit dem Lehrstuhlinhaber und wurde daher Assistent von Paul Scherrer. Zusammen mit Pierre Marmier und Peter Preiswerk beteiligte er sich massgeblich am Bau des ETH-Zyklotrons. Zwischendurch verbrachte er ein Jahr im Hochschulsanatorium Leysin, weil er sich im Militärdienst mit Tuberkulose angesteckt hatte. 1952 schloss er das Studium mit einer Dissertation über Protonen-Neutronen-Reaktionen ab.

Von 1952 bis 1955 weilte Blaser am Carnegie Institute of Technology in Pittsburgh. Am kurz zuvor in Betrieb genommenen 440 MeV-Synchrozyklotron forschte er in der Teilchenphysik, einem Gebiet, das sich aufgrund der neuen Teilchenbeschleuniger in einer stürmischen Entwicklung befand.

1955 wurde er zum Direktor des Observatoire de Neuchâtel berufen, und 1956 zum Professor für Astrophysik an der Université de Neuchâtel. Seine Arbeiten betrafen die Positionsastronomie sowie die neue, auf Atomuhren basierende Standardzeit.

1959 ernannte der Bundesrat Blaser zum Physikprofessor an der ETH Zürich, und zwar als Nachfolger des emeritierten Paul Scherrer. Von diesem übernahm er auch die Zyklotron-Planungsgruppe, an der neben der ETH auch verschiedene Schweizer Universitäten beteiligt waren. Blaser half mit, die Teilchenphysik als Forschungsgebiet in der Schweiz zu etablieren. Von 1962 bis 1970 leitete er das ETH-Labor für Hochenergiephysik, das seine Experimente vor allem am CERN durchführte.

1968 gründete Blaser das Schweizerische Institut für Nuklearforschung (SIN), das im aargauischen Villigen quasi auf die grüne Wiese gebaut wurde. Dieses konzipierte er als eine sogenannte Mesonenfabrik, die von der ETH betrieben wurde, aber allen Physikern der schweizerischen – und später auch ausländischen – Hochschulen als Benützerlabor zur Verfügung stand. Bis 1987 war Blaser der erste (und einzige) Direktor des SIN, das verglichen mit seinen direkten Konkurrenten in Los Alamos (LAMF) und in Vancouver (TRIUMF) grosse Erfolge verzeichnete, indem seine Beschleunigerleistung stets an der Spitze lag.

Ausschlaggebend für den Erfolg war neben Blasers Gespür für neue Entwicklungen sein Talent, junge motivierte Physiker und Ingenieure um sich zu scharen, sie zu begeistern und ihnen einen grosszügigen Freiraum für Ideen zu gewähren. Besonders fruchtbar für das SIN war zudem Blasers Teamarbeit mit seinem Stellvertreter Wilfred Hirt. Frühzeitig erkannte Blaser weitere mögliche Anwendungen für das Protonenzyklotron des SIN, an dem beispielsweise von Anfang an ein Forschungsareal für Krebstherapie mit Teilchenstrahlen eingeplant war.

Dank des Potenzials der Beschleunigeranlagen, Blasers unternehmerischer Vision und der Freiheit beim Einsatz der eigenen Mittel vermochte das SIN neben der hauptsächlichen Teilchenphysik im Mittelenergiebereich laufend weitere Forschungsgebiete zu erschliessen. Diese betrafen ausser der erwähnten Krebstherapie mit Pionen und der medizinischen Positron-Emissions-Tomographie (PET) vor allem die Untersuchung von Materie mittels Neutronen und Myonen sowie Einzelaspekte der Kernfusionstechnik.

Als der Schweizerische Schulrat 1986 vertiefte Studien für die Zukunft der beiden Institute für Nuklearforschung (SIN) und Reaktorforschung (EIR) in Auftrag gab, leitete Blaser das Projekt, das schliesslich zur Fusion der beiden Institute führte. 1988 entstand daraus das Paul Scherrer Institut (PSI). Blaser wurde dessen erster Direktor. Er führte das Institut bis zu seiner Pensionierung im April 1990 und stellte wichtige Weichen bei dessen Neuausrichtung zu einem nationalen, multidisziplinären Zentrum, das zur Aufgabe hat, in enger Zusammenarbeit mit in- und ausländischen Hochschulen Grundlagen- und angewandte Forschung zu betreiben.

Blaser war Mitglied mehrerer wissenschaftlicher Gesellschaften, unter anderem Ehrenmitglied der SPG, und Akademien und erhielt fünf Ehrendoktorate. Mit diesen würdigten vor allem auch Schweizerische Hochschulen Blasers eminenten Beitrag zur Entwicklung der Physik.

Eine bemerkenswerte Eigenschaft von Jean-Pierre Blaser war die Bereitschaft, Aussagen mit physikalischem Hintergrund stets kritisch zu prüfen. Als Professor, der vor allem die Ingenieurstudenten der ETH Physik lehrte, kannte er sich in den physikalischen Gesetzen gründlich aus. Das erlaubte ihm, Behauptungen, die von Gesprächspartnern oder in Medien und Politik geäussert wurden und ihm nicht einleuchteten, schnell nachzurechnen. Lagen die Resultate daneben, äusserte er sich entsprechend – was ihm nicht nur Freunde einbrachte. Blaser vertrat die Ansicht, es sei Aufgabe der Wissenschaft, einzugreifen, wenn die Politik sich auf wissenschaftlich unhaltbare Behauptungen stützte. So befasste er sich gerade in den letzten Jahren seines Lebens auch mit Fragen der Energieversorgung und der Klimaveränderung und äusserte sich dann kritisch, wenn Behauptungen physikalisch nicht oder ungenügend abgestützt waren.

Andreas Pritzker

Progress in Physics (68)

Physics Education Research - An Applied Science (part 2)

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3 Tasks and Services of PER

3.1 Evidence-based (Science) Education

No one would think of getting to the Moon or of wiping out a disease without research. Likewise, one cannot expect reform efforts in education to have significant effects without research-based knowledge to guide them.
R. J. Shavelson & L. Towne (Eds.) [77].

Evidence-based practice in general is the approach to base decisions on the best available evidence, in the sense of the best possible – in particular systematic! – use of existing knowledge and research. Evidence-based (science) education (EB(S)E) follows the example of evidence-based medicine, i.e. "[t]he conscientious, explicit and judicious use of current best evidence in making decisions", as one of its pioneers put it [78].

This is the same basic idea than the "scientific approach to science education" advocated in sect. 2, and indeed in the last two decades, it has led to a very strong current of research and practical implementation of EBSE: For the background in educational science in general work by Hattie [58, 79], based on more than 800 meta-analyses (comprising more than 80 Mio. individuals) is highly influential. Other useful sources are e.g. the "Best Evidence Encyclopedia" of the John Hopkins University [80], and work done at Stanford [77]. For physics and science education, in particular, there are world-class research programs [5, 81] and research syntheses and meta-analyses EBSE are available [82 - 86].

In physics and science education, the evidence-based approach has seen a very strong development in the last decades, and the idea has found strong support among many scientists interested in effective teaching and learning of their disciplines, including work finding recognition at very high level [15, 34, 38]. In particular, the physics Nobel Prize winner C. Wieman has devoted his work in the last decade to PER, [5, 6, 87, 88].

As a word of caution, however, it has to be emphasized that one has to be aware of debate about EB(S)E, raising also critical points [89]. It is certainly not the claim of EBSE to guarantee all by itself a solution to all problems in science education; simplistic recipes are not a goal one is looking for.

Within this rationale, Physics Education Research has the task to contribute to evidence-based decisions, development, initiatives, and teacher education, as illustrated in the first part of the article for the aspects of measurement (e.g. concept tests), interventions (e.g. motivating contexts; active learning approaches for lectures) and influences (e.g. gender). Further examples will be given below.

3.2 Teachers, and Teacher Education

The remarkable feature of the evidence is that the greatest effects on student learning occur when teachers become learners of their own teaching.
J. Hattie [79]

Teacher education has a pivotal role in an educational system: as studies on university level, it is the last stage of an educational trajectory, and at the same time is the basis and starting point for the educational quality for many generations of school students [90].

In order to respond to this pivotal role, it is clear that physics teachers have to be well informed about effective approaches of supporting interest and learning among their pupils, about their relative strengths (sect. 2.2), and about important influencing factors (sect. 2.3). Moreover, they have to be trained to use methods to measure the impact of their teaching (and possible changes) on pupils' motivation and learning, in particular regarding diagnosis of learning difficulties, and the potential impact of methods to overcome them (sect. 2.1). In the sense of Hattie's quote above, taking account of EBSE in teacher education provides a systematic and conscientious base of best evidence for teachers to "become learners of their own teaching". It is a main task of PER to provide a sound physics teacher education and continuous professional development in that spirit. This is well formulated by Robin Millar, a leading physics education researcher in a well-balanced statement [91]: "*We need to work towards a situation in which research evidence is routinely an explicit input to teachers' decision making, but where it is also accepted that this must be weighed judiciously alongside other kinds of knowledge to reach a decision that can be rationally defended.*"

Another reason for the pivotal role of teachers, besides effectiveness, is found at the (inter)personal level. The British UPMAP study (Understanding Participation rates in post-16 Mathematics and Physics) clearly showed that students' relationships with teachers (and other adults) has a decisive impact – through encouragement, advice, or acting as a role – on their decision to choose the subject physics after their mandatory schooling. One example of this from the qualitative data collected for UPMAP is given by [92] in the form of an insightful contrast of good and bad physics teachers, see Figure 5. The studies arrives at an unambiguous conclusion: "*In every case of an undergraduate reading [i.e. studying; AM] physics, their narrative tells that an adult has been significant in their becoming a physics undergraduate. Not peers, not enrichments, interventions or events, but some adult person or people – usually teachers or family members*". This result is complemented by the quantitative results [93] where encouragement is found to be the

Statement about a good science teacher [92]

I: Going back, you said you had a very good teacher at GCSE, what was good about him or her?

S: She was very good at making it interesting, she made the lessons fun and I suppose I got on with her on a personal level so that helped and she was very encouraging.

The same female pupil about a bad science teacher:

S: He was bad because he didn't know my name for maybe nine months and he didn't pay any attention... it got to a point where I wouldn't go to the lessons sometimes and would teach myself from the books.

Statements about the importance of role models [94]

"My math and science teachers were always important role models in my life. My parents wanted me to go into business or something like that."

"I think that one of the reasons why I chose math and science and chose engineering was because I had a teacher that was female. So if there was more females in engineering that could teach, it would make a big difference."

Figure 5: Encouragement, advice, role model: Importance of science teachers on the (inter)personal level, according to female students (I: Interviewer, S: student).

teacher variable with the strongest influence on the choice of physics (correlation $r = 0.5$), well ahead of all other factors. UPMAP is one of the broadest studies on this question (qualitative and quantitative student parts, $N > 5000$), and its results agree with the state of knowledge drawn from many other studies. When it comes to choosing an academic or vocational career in STEM (Science, Technology, Engineering, Mathematics) fields, research [94 - 98], including taking into account female students' own reports [95], consistently shows that discipline-specific self-concept is a decisive factor, as well as the availability of role models for [female] school students and students. See Figure 5 for a few more statements supporting this.

In line with the decisive role of teachers, the UK Institute of Physics (IOP) has developed in the last decades exemplary programs for initial and continuous physics teacher education [99]. In German speaking Switzerland, SWISE [1] has provided support for the improvement of teaching for general Science and up to secondary level I. The Swiss Physical Society, with a financial support by SCNAT, has recently initiated first steps towards a program for Swiss Physics Teachers.

1 Swiss Science Education, https://swise.ch/

3.3 Development

Another important task of PER is the development of new and innovative teaching and learning materials and ideas on all educational levels. A first type of this kind of work is the development of new experiments for educational purposes, with a range between surprising effects and insightful, in-depth analysis (Figure 6, a and b; respectively). Closely related is a second area – hands-on and "everyday" physics (physics of everyday phenomena), such as the famous "Flying Circus of Physics" by J. Walker [100], "La Physique du Quotidien" by I. Berkes [101], or the work by H.-J. Schlichting [102]. Figure 6c shows a nice simulation experiment of a potential explanation of the Bermuda triangle myth; even though today one knows that there is no conspicuous number of disasters in this high-traffic area, the example shows how physics can provide natural explanations without invoking any hocus-pocus.

Third, innovative approaches using new technology, such as ICT and multimedia, but also e.g. thermal cameras (see e.g. Figure 6b and extended work by Vollmer, see e.g. [107]). A recent review [108] presents almost 500 contributions oriented towards physics teaching practice from 10 European countries, with a perspective of finding ways of cross-language and cross-country use of the educational potential of this wealth of work. A particularly strong and stimulating development of the last decade is the use of smartphones (and tablets) as portable laboratories (see e.g. article series in "The Physics Teacher", [109]). They allow to extent physics education from the classroom to almost everywhere, where learners can investigate scientific phenomena in real life contexts (see 2.2). This covers a whole range from standard topics of physics education (inclined plane, rotations, energy conservation in novel settings (e.g. vertical jump, [110]) to more explorative experiments such as about knuckle-cracking (Figure 6d, [106]), pressure wave in tunnels [111], oscillations of elevators [112], and more, and from school to university [113]. Beyond a wealth of physics applications provided by this approach, recent PER studies have also provided evidence about positive impact on learning and motivation [114, 115].

A fourth important area of development are simplified approaches to interesting, but partially difficult topics, in particular modern physics, i.e. offers for physics communication ("popular science") and education. This requires a detailed

American Journal of Physics (U*(**))	Forinash, K., & Whitten, B. (2019). Resource Letter TEP-1: Resources for Teaching Environmental Physics. Am. J. Phys. **87**(6), 421-432. Henderson, C., Khan, R., & Dancy, M. (2018). Will my student evaluations decrease if I adopt an active learning instructional strategy?. Am. J. Phys., **86**(12), 934-942.
Bulletin de l'union des physiciens (BUP) (S*)	Médjahdi, K. (2018) Durée de vie d'un état excité... au lycée ! BUP (112) 1325-1332
Der Mathematisch-Naturwissenschaftliche Unterricht (S*)	Böttche, B. (4/2018) Über die Lebensdauer von Seifenblasen - eine Exponentialverteilung im Experiment. MNU **71**(4), 239-241
European Journal of Physics (U*(**))	Seyfarth, A., & Schumacher, C. (2019). Teaching locomotion biomechanics-From concepts to applications. Eur. J. of Phys. **40**(2) 024004
Physical Review – Physics Education Research (U**)	Wulff, P., Hazari, Z., Petersen, S., & Neumann, K. (2018). Engaging young women in physics: An intervention to support young women's physics identity development. Phys. Rev. PER **14**(2), 020113.
Physics Education (S*)	Bezerra, A. Z. L. N., et al. (2019). Using an Arduino to demonstrate Faraday's law. Phys. Educ., **54**(4), 043011.
The Physics Teacher (S, U*(**))	Babbs, C. F. (2019). Stone Skipping Physics. The Physics Teacher, **57**(5), 278-281.

Table 3: Some useful journals in the area of physics education with an example of a current contribution of interest (S, U: school and university level, respectively; focus on development and research**)*

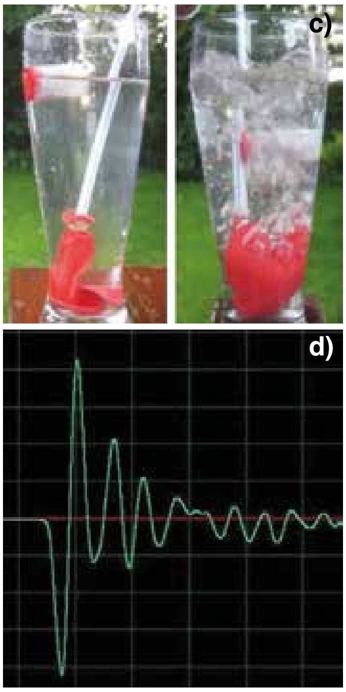

Figure 6: PER and development of teaching ideas
a) Interleave the pages of two paperback books in a way that the pages of the one book overlap with those of the other by at least 10 cm (card players know a similar way of shuffling). Now try to pull the books apart as shown – it is impossible! [103]
b) IR images and selective absorption for a plastic curtain (an analogy to IR images looking behind the "interstellar dust" curtain of the milky way [104]
c) Bermuda triangle analogy experiment: decrease of buoyancy by gas bubbles [105]
d) Knuckle cracking – actually an oscillation in the kHz range (recorded with smartphone app) [106]

understanding of the previous knowledge, conceptual obstacles, and a realistic difficulty level for different target audiences, which can be provided by PER (see 2.1). In view of attracting young people to physics related school programs and careers, educational material for high schools is of particular interest (see e.g. next section for activities and a book on cosmology and general relativity for (senior) high school, and Table 3 for some other recent examples of this kind from PER journals.

3.4 Service

Last, but not least there are various kinds of services PER has to render to physics departments and institutions. A very important topic for this is their engagement for science communication, and in particular for encouraging young people, in particular women, to study physics. PER can advise on evidence – good practice and research – from other institutions, provide ideas and suggestions for promising initiatives, and eventually help to evaluate them once realized. It goes without saying that strong cooperation with science communication units is a strong factor of success. Some examples:

First, programs of anticipated studies as those offered in Germany and in Switzerland by the University of Geneva (program "Athena" [116])[2]. The idea is to open regular university courses to pupils of the last classes before the matura, with the aim of offering an opportunity of exploration, orientation and inspiration for university studies in physics (and other disciplines). These programs work quite well, as e.g. indicators from the Athena program show (see Figure 7, [116]).

Second, input and support for out-of-school learning offers such as the S'CoolLAB of CERN or the other examples in Table 4, which provide a broad and high quality spectrum of different foci and formats, with the aim to foster a positive attitude and understanding of science among the population in general, and young people in particular. The input and support provided by PER concerns educational concepts, evaluation, realisation of projects, and funding requests. In this sense, a series of PhD theses at or in cooperation with the PER group in Geneva looks into evaluation and optimising design of out-of-school learning offers; for the S'CoolLab it could e.g. be shown that current interest and conceptual understanding (focus: electromagnetic fields, particles, radiation) are notably increased (*ES* = 0.59, *ES* = 0.75, respectively; [117]). A particular offer of cooperative out-of-school learning offer is the Stellarium Gornergrat (Figure 7b), a

2 Frühstudium (D): https://www.telekom-stiftung.de/projekte/fruehstudium; Athéna (Unige): https://www.unige.ch/sciences/fr/faculteetcite/programme-athena/

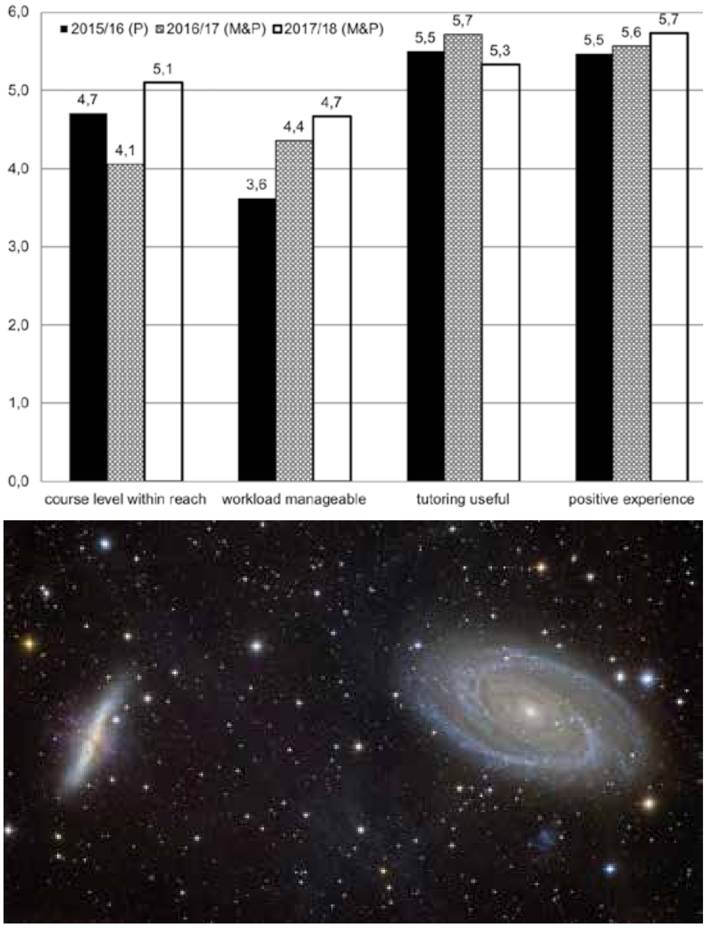

Figure 7: PER service to physics departments and institutions
a) Basic indicators of feasibility and impact of the Athena program according to average responses by participants (scale from 1= lowest to 6 = strongest consent; P: physics, M: mathematics)
b) Image from the module „Galaxy Zoo" of the Stellarium Gornergrat, an offer of largely unprecedented quality for educational purposes.

DeltaX: science education lab for lower and upper secondary level and physics, chemistry or biology	Helmholtz-Zentrum Dresden-Rossendorf *https://www.hzdr.de/db/Cms?pNid=1623*
iLab: science education lab mainly for lower secondary level and physics, close link to PSI research (e.g. combination with guided tours)	Paul Scherrer Institute, Villigen *https://www.psi.ch/de/ilab*
mobiLLab: mobile high-tech laboratory with 12 work stations for lower secondary schools	Teacher University St. Gallen *https://www.phsg.ch/en/research/projects/mobillab*
Scienscope: science education and outreach centre for all age groups and 7 scientific disciplines (chemistry, biology, earth sciences, informatics, mathematics, physics and astronomy)	Faculty of Science, University of Geneva *https://scienscope.unige.ch/*
S'Cool LAB: physics education lab with a focus on CERN-related physics for upper secondary level	CERN, Geneva *http://scool.web.cern.ch/*

Table 4: Physics and science out-of-school learning offers

remote-access observatory for educational purposes run in cooperation by astronomers in Bern and Geneva, and the Geneva PER Group, which exploits the high motivational potential of astronomical topics (see 2.2) by integrating them in regular physics (and mathematics) lessons [118]. This work is carried out by an active high school teacher, Stéphane Gschwind, who is key to ensure adaption to the target audience (content difficulty, language level) and to study plans, for testing activities in test classes, for support to collegues interested to use the Stellarium, for continuing development courses and for actively promoting the project through professional networks.

Third, cooperation within the "communication/education" sections of large national and international research programs. For instance, within the National Centre of Competence in Research (NCCR) SwissMAP (The Mathematics of Physics, [119]), there was a request for an educational project launched on the occasion of the centenary of Einstein's general theory of relativity. Alice Gasparini, physicist and active high school teacher, has developed a learning sequence about cosmology and general relativity for high schools students providing access to the essential physical ideas of these fascinating topics, strictly using mathematical tools available at school. All material is accessible for teachers at a website, and also as a printed book [119 - 121].

4 Conclusions, Perspectives

As shown by the examples above, evidence-based approaches in PER – measurement methods, results on teaching interventions and understanding of influences – play an essential role in science communication, teaching practice and teacher education in our discipline. As stated several times, they are proposed as examples of good practice, but it is not claimed that they are ideal, nor the only ones. Moreover, there are important aspects which were not discussed in this article due to lack of space, especially the extremely fruitful connections between physics education and history and philosophy of physics, e.g. the many interesting contributions in this journal [122], in particular by J. Lacki, or the very nice book for the general public on the conceptual underpinnings of quantum information theory by N. Gisin [123].

As an applied science, PER systematically links research with development and other practical tasks and services (see examples in sect. 3). PER is about research-based development, and practice-inspired research in the area of physics education. These two elements sometimes face prejudice from scientists. On the one hand, it is not uncommon that scientists believe that physics education is an opinion based rather than an evidence-based discipline. On the other hand, few have first-hands experience with the application of PER results in their own teaching practice. They might thus not be convinced of their usefulness. It was one purpose of the article to provide arguments and examples that the prejudice mentioned is unfounded.

Research-based development, and practice-inspired research in the area of physics education are not unimportant objectives, nor trivial ones. A major obstacle is insufficient interaction between research and (teaching) practice. For instance, in the review on ICT uses in physics teacher journals [108], less than 10% refer in any form to underlying educational research (e.g. potential to overcome misconceptions or to foster motivation). ICT application in physics education is a technologically highly innovative area, but it appears as largely disconnected from physics education research – something unthinkable in engineering or medicine. One condition to overcome this "implementation gap" is a strong and systematic cooperation of PER with active teachers, in research, development and teacher education.

Another condition is about the role of PER in academic structures. If universities, as strongholds of culture and science in a society, want to ensure the transmission of their values and knowledge, in order to have good students and to ensure the academic succession, but also for the development of society in general, they have to strongly engage themselves for Evidence-Based Education, in particular concerning teacher education. This implies a systematic and reliable positioning of physics (science) education in academic structures, either by PER groups integrated in physics departments, or by institutional partnerships between physics departments and physics/science education groups at teacher education universities. This is the only way to ensure continuous integration of modern physics, cooperation for outreach initiatives of physics institutions, long-lasting collaborations with active teachers and a research basis for physics teaching at school and physics teacher education, and thus to ensure educational quality for many generations of school students.

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Kurzmitteilung

Vorankündigung "Jean-Pierre Blaser Gedächtnissymposium"

Der hochverehrte und leider jüngst verstorbene Kollege Jean-Pierre Blaser hat die Physikforschung der Schweiz nachhaltig geprägt (siehe Nachruf auf Seite 24). Eine Organisationsgruppe um die Herren Ralph Eichler und Hans-Rudolf Ott plant deshalb ein "Jean-Pierre Blaser Gedächtnissymposium" in Zürch im ersten Quartal 2020. Es soll in mehreren Vorträgen an die technischen, wissenschaftlichen und geschichtlichen Entwicklungen am SIN und während der Anfangsjahre am PSI erinnert werden. Die Schweizerische Physikalische Gesellschaft (SPG) und die Physikalische Gesellschaft Zürich (PGZ) übernehmen gerne das Patronat der Veranstaltung. Genaueres erfahren Sie anfangs 2020 auf den SPG und PGZ Webseiten, sowie im SPG-Newsletter. Die Organisatoren würden sich über eine zahlreiche Teilnahme freuen.

Progress in Physics (69)

It's All in the Shape: Triangularity on TCV

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In magnetically confined fusion plasma science, the tokamak – a toroidal plasma confining device - has the potential to provide confinement sufficiently high to sustain thermonuclear fusion reactions. As such, the tokamak may be the basis for electricity production based on the fusion of the isotopes of hydrogen. However, in the standard tokamak configuration (see Figure 1b), in order to achieve sufficiently high energy-confinement the edge plasma pressure must be very high. As a result, the edge pressure gradient is also large, and this leads to instability that repetitively ejects particles and energy, which can potentially damage the plasma facing wall in a fusion reactor [1]. There may be a very simple solution to the problem. By inverting the geometry of the magnetic configuration, going from (b) to (a) in Figure 1, we change triangularity (δ) from positive to negative and in so doing the energy confinement time typically doubles; a discovery made on the TCV tokamak. At the same time, the edge pressure gradient remains sufficiently low that the instabilities, mentioned above, become much smaller or do not appear at all [2]. This article, very briefly, describes the work, performed on the Tokamak à Configuration Variable (TCV) at the Ecole Polytechnique Fédérale de Lausanne, in the field of negative triangularity tokamak. Some attempt will be made to put TCV's results in relation to observations on other machines and in the context of a reactor device.

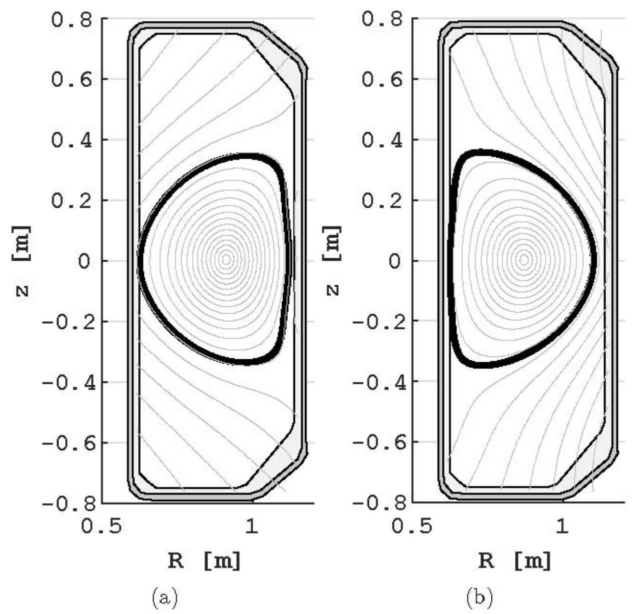

Figure 1: Two cross-sections of TCV, torus axis on the left, showing the plasma inside the TCV vacuum vessel, for two similar discharges, (a) has negative triangularity while (b) exhibits positive triangularity – the standard plasma shape in tokamaks. Apart from this difference in geometry, the discharges are very similar in terms of plasma current, vertical elongation, density etc.

TCV was conceived as a machine for testing the effect of plasma shape on energy/particle confinement and on plasma stability. As such it was endowed with many independently controlled shaping coils allowing for a myriad of exotically shaped plasmas to be created in the device – most of them having never been explored. In addition to this shaping flexibility, TCV has electron and ion heating capabilities that allow the study of transport in different regimes of plasma collisionality and ratio of electron to ion temperature T_e / T_i. These two parameters are decisive in determining the type of unstable modes and growth rate underlying turbulence, therefore, the amount of heat and particles that the plasma loses by transport.

TCV has much greater plasma shaping capability than any other existing machine. Making use of this advantage, a great deal of effort has gone into characterising the effects of triangularity, which has been found to play an important role in plasma confinement and in plasma stability [3, 4, 5]. It may, in principle, be used to actively control both confinement and stability.

The work of Moret [3], finding confinement increasing by diminishing δ in the positive triangularity range, could be prolonged to negative triangularity with stable discharges in additional heating conditions by Pochelon [6]. With his student Camenen [7], they studied the effect of triangularity on transport, comparing positive and negative δ. They, in turn, stimulated more recent work concentrating on the effect of triangularity on turbulence: the main drive for energy loss in magnetically confined fusion plasmas. Turbulence measurements culminated in the work of De Meijere [8], Huang [9] and Fontana [10]. At the same time Sauter [11] and Merle [12] studied the edge plasma properties showing, clearly, its important role. In parallel with the experiments a significant

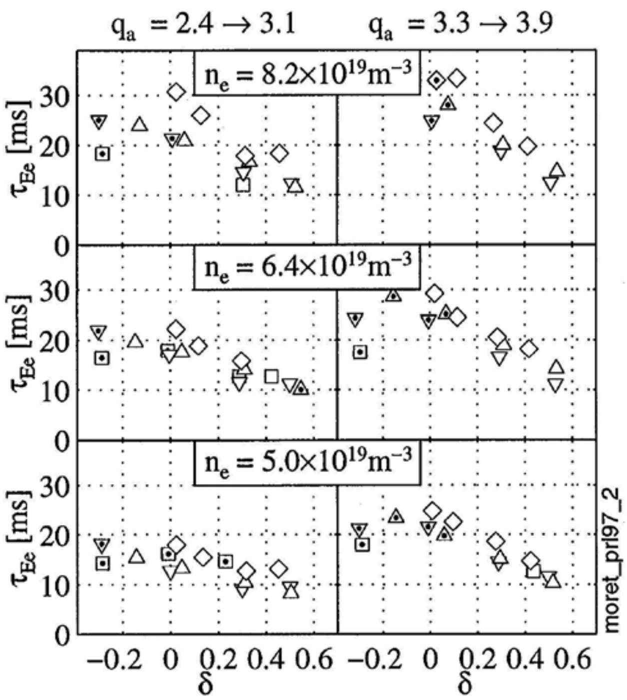

Figure 2: For various values of electron density and q_a, energy confinement time is seen to increase as delta decreases in the positive delta range. q_a is proportional to plasma current and is linked to stability of the plasma.

effort has been made to model these discharges on a microscopic, turbulence scale using fully electromagnetic, fluid and kinetic codes. The simulations are at least in qualitative agreement with experimental findings [13, 14].

Moret [3] first observed an improvement of confinement towards small positive triangularity with less clear behaviour at negative triangularity, see Figure 2, and ascribed the improvement to purely geometric effects. Pochelon [6] pursued these studies with electron cyclotron resonance heating (ECRH), enabling more stable discharges.

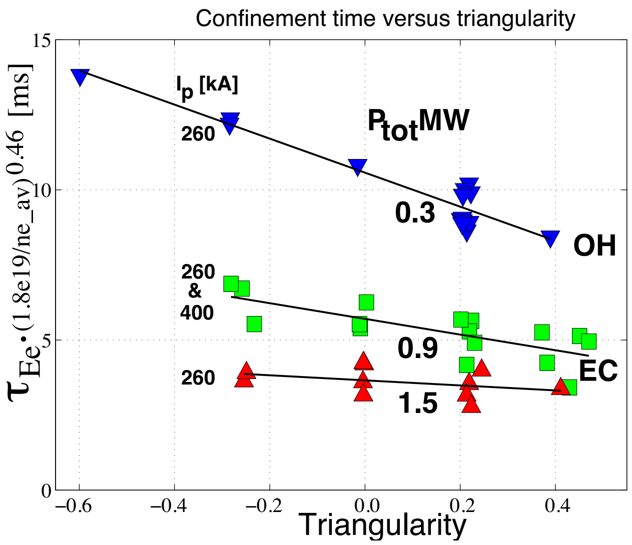

Figure 3: Linear increase in confinement extending to the negative triangularity range at low density, in Ohmic and with ECR heating.

These experiments revealed for the first time a clear continuous improvement of confinement time far in the negative triangularity range down to δ = -0.6 [6], as shown in Figure 3. This showed how existing scaling laws were improved by decreasing triangularity δ. The negative triangularity results indicated also that there was a more fundamental confinement improvement, beyond purely geometrical effects.

Camenen [7] completed a thorough and exhaustive study of the effect of triangularity on heat transport using modulated ECRH power. He produced the, now famous, figure relating electron thermal diffusivity (χ_e), effective collisionality (υ_{eff}) and δ. Figure 4 reproduces Camenen's figure, showing the factor of 2 decrease of the electron thermal diffusion coefficient over a large range of υ_{eff} between discharges at δ ≈ +0.4 and δ ≈ -0.4 with the improvement diminishing at high υ_{eff}. The reduction of the relative superiority of negative δ discharges at high collisionalty may explain the relatively weak effect at negative δ seen by Moret.

Camenen's work was performed in conditions where $T_e >> T_i$ and a specific type of plasma instabilty, the trapped electron mode (TEM), was the dominant unstable mode and driver of transport. Marinoni [13] modelled these discharges using both linear and non-linear local gyrokinetic simulations using state of the art modelling tools [15]. He was able to reproduce the trend of diminishing χ_e as δ decreased. The physical mechanism for the confinement improvement was postulated to be a complex interplay between particle motion in the non-homogeneous magnetic field of a tokamak that leads to particles being trapped in magnetic wells or being free to propagate along the field lines. The change in the curvature introduced by negative δ modifies the toroidal precession drift of the trapped particles. As the TEM is intrinsically linked to the resonance with the toroidal precession drift, this modification affects the radial transport.

So, it had been shown that, over a wide range of υ_{eff} , by inverting the triangularity, the energy confinement was improved by up to a factor 2 when $T_e >> T_i$ and when a particular type of instability was driving plasma turbulence and diffusion of energy. Theory had been able to, at least qualitatively, offer some explanation for the improvement of energy confinement at reduced or negative triangularity.

It is assumed that plasma turbulence drives energy and particle diffusion, since transport in tokamaks is at least an order of magnitude higher than calculated from particule trajectories and collisions, so-called neoclassical transport.

Further, in a fusion reactor it is necessary that $T_i \approx T_e$. In this circumstance different plasma instabilities are excited and the transport properties of plasma change. It is not obvious

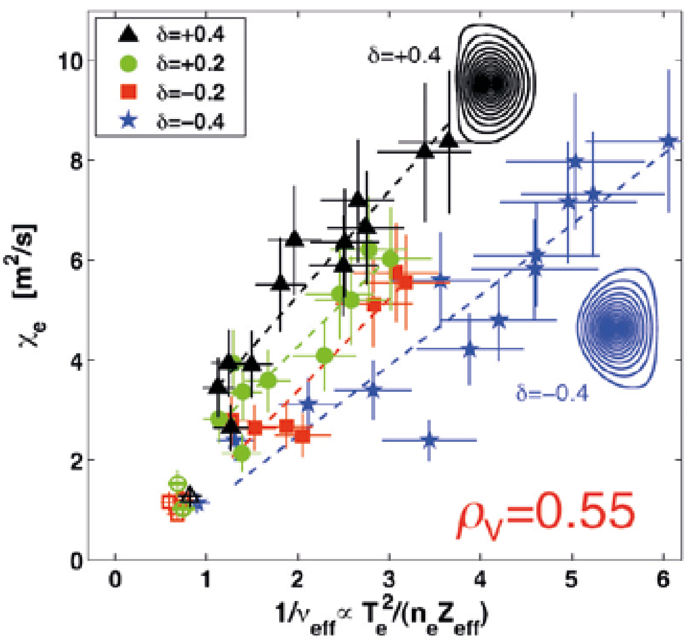

Figure 4: Decrease in the experimental χ_e with decreasing δ in ECR heated plasmas.

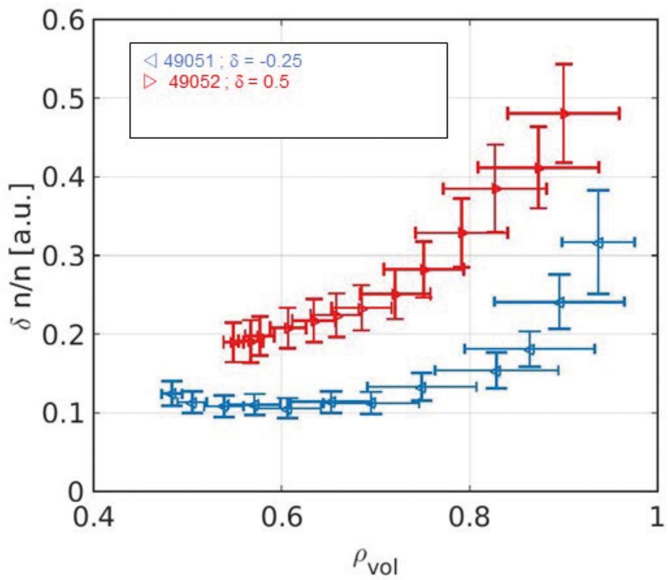

Figure 5: Relative density fluctuation amplitude ñ/n as a function of radial position in a δ = 0.5 (blue) and a δ = −0.25 (red) TCV discharge; both discharges have 0.45 MW EC heating at the plasma center (ρ_{vol} = 0: plasma center, ρ_{vol} = 1: plasma edge).

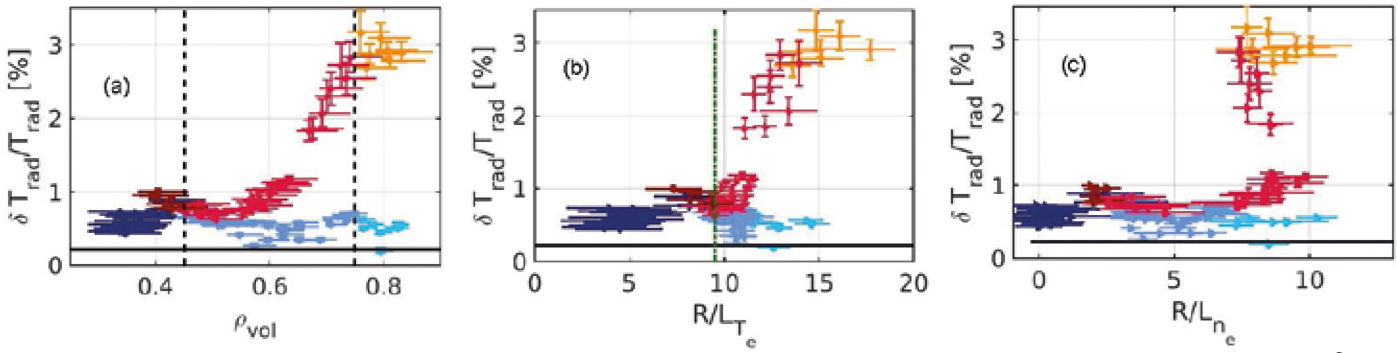

Figure 6: a) Radial profiles of relative radiative temperature fluctuations amplitude for different triangularity values. (red/yellow δ ≈ 0.5: blue δ ≈ -0.4) The fluctuations amplitude is reduced changing shape from positive to negative triangularity and the effects extend up to ρ_{vol} = 0.5. The same data are plotted against the normalized inverse temperature (b) and density (c) scale lengths. Notice that these data points combine measurements taken over a wide fraction of the radius.

that negative δ will maintain its advantage in reactor relevant conditions.

These two observations lead immediately to two questions concerning negative δ:

(i) Is there a connection between the improved confinement at negative δ and the measured turbulence?

(ii) Does the improvement of energy confinement at negative δ persist when $T_i \approx T_e$?

Huang [9] and Fontana [10] addressed these two questions experimentally making very detailed measurements over a wide range of plasma conditions allowing a large database to be constructed.

Figure 5 shows the reduction in relative density fluctuation amplitude across a large section of the plasma minor radius in discharges that are similar apart from δ [9]. In Figure 6 are plotted profiles of $\widetilde{T_{rad}}/T_{rad}$ plotted against normalised radius (a), and normalised density- (b) and temperature- (c) -scale lengths. Red/yellow is for positive δ while blue is negative δ. So we see a clear reduction of both density and temperature fluctuations across a substantial portion of the plasma radius in negative δ. At the same time there is the suggestion that in positive triangularity, there may be a critical gradient in either temperature or density above which the instability and fluctuations can grow [10]. There is no such critical gradient in the negative δ data; it may be that the critical gradient for the onset of instability is much higher in negative δ than in positive δ. Similar observations were made in the density fluctuation data [9]. Merlo [14], using the GENE code, was able to qualitatively reproduce these observations using local, non-linear simulations of theses discharges. He observed a global reduction of the growth rate of instability and a significant increase of the critical gradient for the onset of instability at negative δ compared to positive δ, and that the critical gradients increased even further the closer to the plasma edge. The reduction in fluctuation level going from postive to negative δ are consistent with the observed improvement in energy confinement in the same circumstance.

Fontana was able to extend the database to cases where $T_i \approx T_e$. He observed that the reduction in fluctuation level was preserved even at elevated T_i; this is to say in fusion relevant conditions.

It is clear that negative triangularity can improve confinement over a wide range of plasma conditions including conditions approaching reactor relevance. Why is confinement improving and where is confinement improved?

Sauter [11] has completed an extensive study of profile stiffness, which is the tendance of a magnetised plasma to resist temperature peaking in the presence of central heating. Sauter's work has shown that the core of a magnetised plasma exhibits stiff profiles meaning that the transport gradients of magnetised plasma remain similar irrespective of the plasma heating regime. Sauter's startling observation was that the confinement properties of tokamak discharges are governed by the plasma edge and it is the change to the edge profiles and transport characteristics induced by negative δ that drive the confinement improvement.

The confinement improvement localised to the plasma edge is, in fact, a phenomenon already observed in tokamak physics and is usually associated with high edge plasma pressure gradients as mentioned at the beginning of this article. In the case of high edge pressure the improved confinement is called H-mode (H for high) and is observed in both positive and negative δ. The question then is, in H-mode does negative δ display improved characteristics compared to positive δ? More to the point, are the instabilities, associated with H-mode, less harmful in negative δ

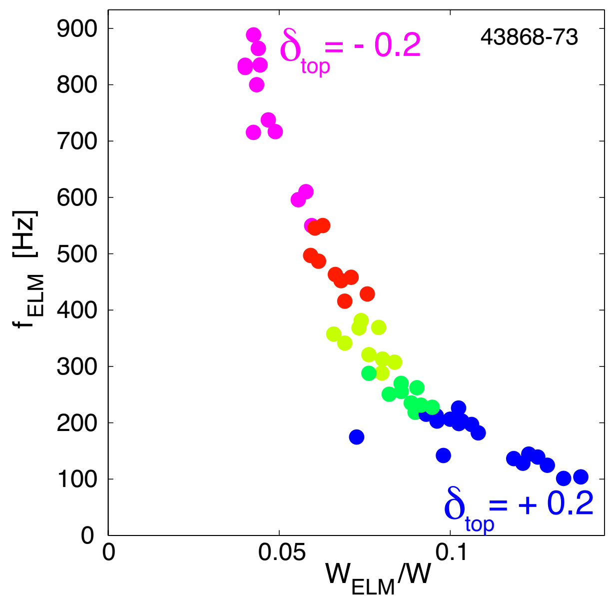

Figure 7: Plot of ELM frequency against energy loss per ELM. There is a clear reduction of the relative energy loss per ELM in negative δ associated to a frequency increase.

than in positive δ? Pochelon [2] was the first to study this issue. He showed that, for similar conditions, the frequency of the instabilities (Edge Localised Modes: ELMs) was increased and that the energy loss per ELM was significantly reduced in negative δ. The result is shown in Figure 7.

Merle [12] completed a theoretical study of the edge pressure in H-mode and, reassuringly, predicted that the edge pressure, and therefore the energy release per ELM, would be reduced by factor 4 in negative δ compared to positive δ. At the same time he stated that the reduced pressure made any large ELM event impossible.

Recent work performed at DIII-D, a conventional tokamak in America, showed that in negative triangularity it was possible to achieve high confinement and performance in discharges where in positive triangularity, the performance would have been a factor of 2 poorer (see Figure 8). This without degradation of energy confinement with additional heating power. It is a very significant result as it points to the possibility of creating high power, high confinement fusion plasma without the need for very high edge pressure and edge pressure gradient.

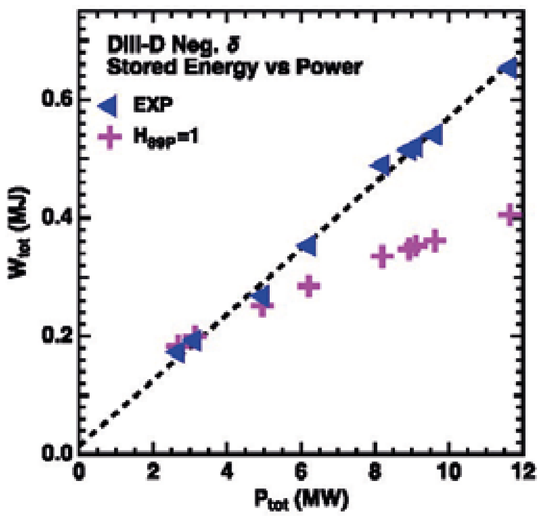

Figure 8: Confined thermal energy against additional heating power showing the absence of degradation with heating power. Confinement is comparable with H-mode confinement but with an L-mode edge (L for low confinement). The blue triangles represent the experimentally measured stored energy while the magenta crosses show the expected stored energy from empirical scaling laws with standard positive triangularity. Negative triangularity clearly exhibits superior confinement properties.

So we see that negative triangularity has some specific benefits for magnetic confinement fusion: high energy confinement with a low pressure and so with no ELMs.

Besides these important physics benefits, there are several potential engineering advantages to using negative triangularity. The part of the chamber wall which would be exposed to the most particle and energy flux, the so-called divertor can be placed at large major radius. Therefore its surface area is large, compared to positive triangularity, and the exhaust can in principle be deposited over larger surface (~2πR). At the same time the engineering problems associated with a low field side divertor as compared to a high field side divertor are much reduced. It is much easier to design a low field side divertor and the means to remove it and replace it when needed as compared to a high field side divertor.

It sounds as if negative triangularity is the long sought panacea for magnetic fusion: low edge pressure with, at the same time, high energy confinement and no edge instalibilities and reduced tendence to generate internal perturbations. There are, of course, many questions that remain to be answered and there may be drawbacks.

We know that it is difficult to control the vertical position of negative triangularity discharges in the vacuum vessel. In fact they are notoriously unstable [16]. To date it has proven extremely difficult to achieve high performance negative triangularity discharges with a divertor. In cases where diverted discharges have been produced, measurements show that the area over which energy is deposited on the divertor tiles is substantially reduced and may negate any advantage of having a divertor at larger major radius [17]. The design of magnetic coils for a negative triangularity machine may be very difficult and may require use of coils that will have a reduced lifetime as compared to a normal tokamak.

All of these issues are being addressed in Switzerland and all over Europe. Only time and extensive experimentation will tell if negative triangularity will lead to a robust solution for magnetic fusion. Switzerland is leading the way in these studies.

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Progress in Physics (70)

Chiral twist in mesoscopic magnetic systems

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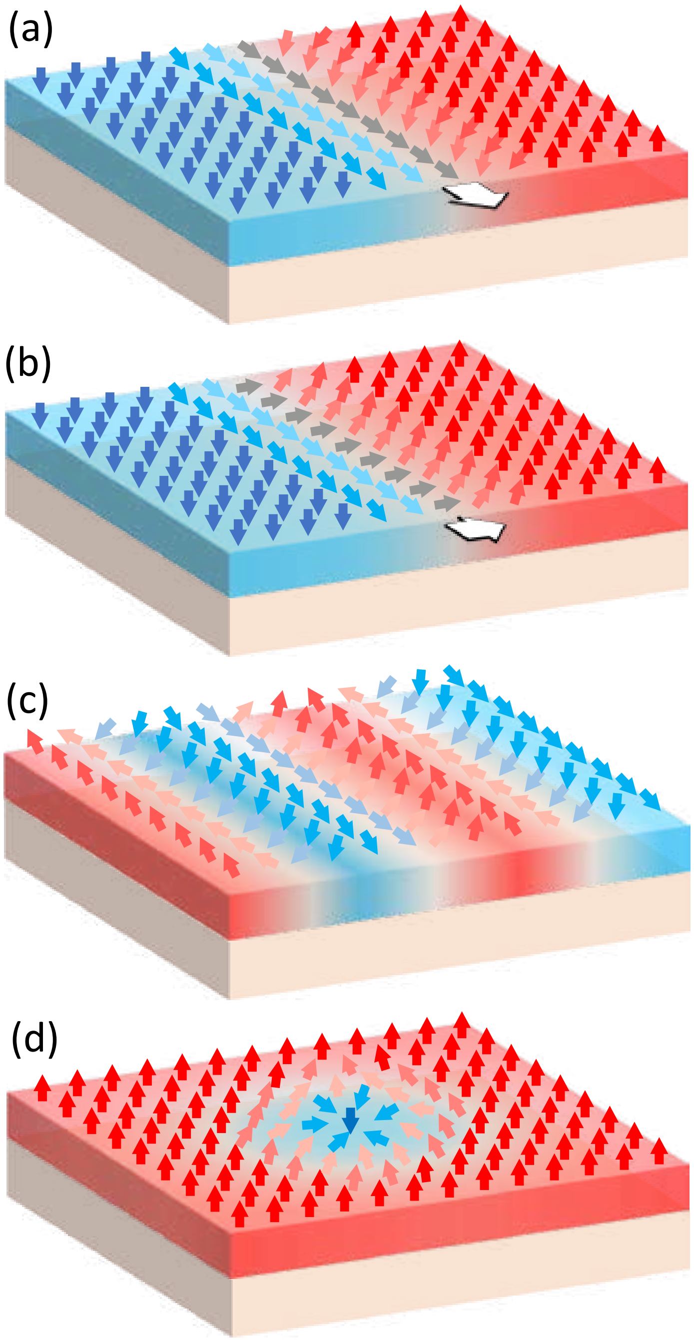
Chiral coupling on the atomic scale

The Heisenberg exchange interaction lies at the heart of magnetism since it is responsible for the collinear alignment of the magnetic moments of neighbouring atoms. It is usually represented by the Hamiltonian $J\,\boldsymbol{m}_i \cdot \boldsymbol{m}_j$, where the sign of the exchange constant J dictates whether the magnetic order is ferromagnetic or antiferromagnetic in nature. In the 1950s, based on symmetry arguments, Igor Dzyaloshinskii and Toru Moriya deduced a new type of interaction between two neighbouring spins leading to their non-collinear alignment. The key ingredients are a strong spin-orbit coupling, which links the electron spin to the atomic lattice, and a broken structure-inversion symmetry that naturally occurs at surfaces and interfaces. This interaction is generally expressed as $-\boldsymbol{D}_{ij} \cdot (\boldsymbol{m}_i \times \boldsymbol{m}_j)$ where D is the Dzyaloshinskii-Moriya interaction (DMI) constant and its vector orientation reflects the symmetry of the system [1]. Experimental signatures of this interaction were first revealed in weak ferromagnets and antiferromagnets, and seemed to be only relevant for a restricted class of materials [2,3]. However, with the advent of ultrathin magnetic films and their implementation in spintronics, it was realised that this interaction can play a key role in technologically relevant systems [4,5].



In thin films, the interfacial DMI can cause a twist of magnetic domain walls from a magnetostatically stable Bloch configuration (Fig.1a) into a Néel configuration with fixed chirality (Fig. 1b), and ultimately stabilize non-collinear magnetic order such as spin spirals or skyrmions [8] (Fig. 1c and d). This seemingly unimportant twist has profound consequences on the domain wall dynamics [9]. Indeed, their miniscule size and sensitivity to the electric currents, make domain walls attractive as nanoscopic information carriers in data storage devices [7]. We show here how the DMI can be tuned and exploited to create artificial magnetic systems on different length scales, opening new opportunities to study topological spin textures and to control the magnetization dynamics of nanoscale magnets.

Chiral coupling on the mesoscopic scale

The size of the magnetic textures such as domain walls, skyrmions or cycloids is naturally defined in magnetic materials and thus limited by the interplay between the competing magnetic energies. Here, we exploit these natural length scales in artificial mesoscopic structures, placing the $-\boldsymbol{D}_{ij} \cdot (\boldsymbol{m}_i \times \boldsymbol{m}_j)$ twist in particular locations to give novel magnetic configurations and effects. The artificial structures are composed of regions with out-of-plane and in-plane magnetic anisotropies as illustrated in Fig. 2a, fabricated using advanced lithography techniques. Pt(6 nm)\Co(1.6 nm)\Al films were deposited onto silicon substrates using magnetron sputtering and consequently patterned into nanoscale islands. Due to the shape anisotropy and a low effective interfacial anisotropy arising from the lower Pt\Co interface,

Figure 1: Magnetic domain walls in out-of-plane magnetized films. (a) Films in the absence of DMI contain achiral Bloch walls stabilized by internal domain wall anisotropy. In this case, the magnetization in the centre of a domain wall lies along the domain wall. (b) If DMI is present and is high enough to overcome the internal domain wall anisotropy, a Néel wall of a fixed chirality (i.e. fixed sense of rotation as one goes across the domain wall) becomes stable. Here, the magnetization in the centre of the domain wall is perpendicular to the domain wall. If DMI is strong enough, it can bring the ground state into (c) a spin spiral or (d) a skyrmions state.

the magnetization orientation is confined in the film plane. In order to obtain perpendicular magnetic anisotropy, we add a $Co\backslash AlO_x$ upper interface [10]. This can be achieved by a controlled oxidation of the aluminium top layer. A selective oxidation is realized using a mask during the oxidation process that protects the parts of the structure where the magnetic easy axis remains within the film plane. Crucially, due to the combination of high spin-orbit coupling and broken inversion symmetry, the Pt\Co interface serves as a source of the aforementioned DMI. This interaction provides an essential connection between the in-plane and out-of-plane magnetized parts of the structure, which would otherwise only be coupled via non-chiral exchange and dipolar interactions.

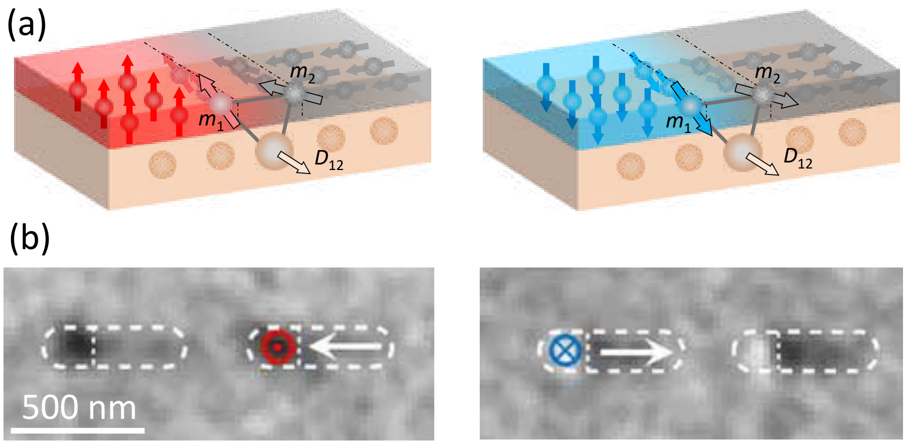
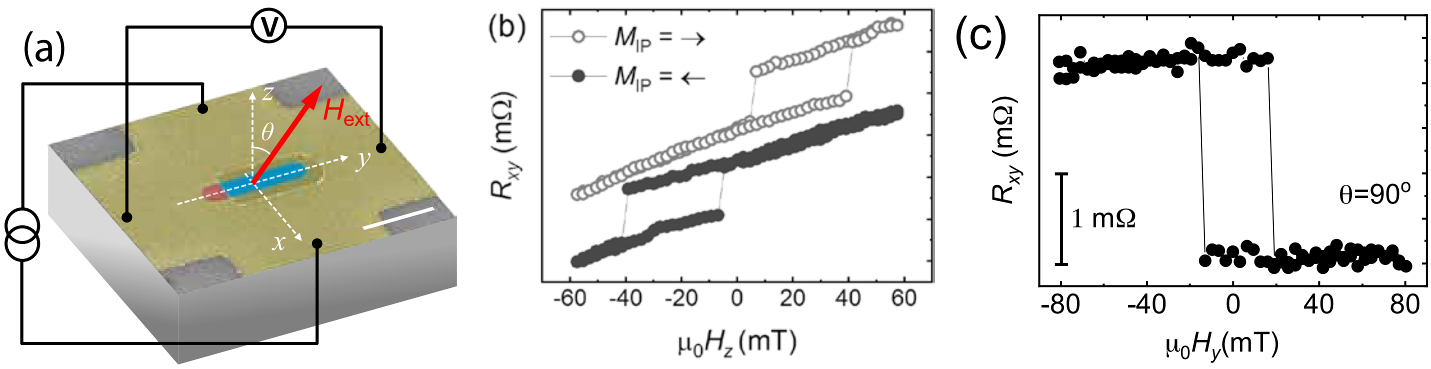


Figure 2: (a) Schematics of the hybrid magnetic systems composed of coupled out-of-plane and in-plane magnetized regions. DMI in Pt\Co layers prefers a left-handed chiral ordering of the magnetization, i.e. up-left (left panel) or down-right (right panel). (b) X-PEEM images corresponding to the magnetization configuration depicted in (a). The dark and bright contrast in the out-of-plane regions corresponds to ↑ and ↓ states, respectively. The dark and light grey contrast in the IP magnetized parts corresponds to → and ← magnetization, respectively. From [16]. Reprinted with permission from AAAS.

Due to the size of the fabricated patterns, which are below resolution of conventional microscopy techniques, we investigated the chirally coupled structures with x-ray photoemission electron microscopy (X-PEEM) at the SIM Beamline, Swiss Light Source. Since X-PEEM is sensitive to the projection of the magnetization direction along the incident x-ray direction, the contrast simultaneously provides information on the orientation of the out-of-plane and in-plane magnetized parts of the structure. In Fig. 2b, the magnetic state has been initialized with an in-plane magnetic field prior to the imaging. When the magnetization of the in-plane element $\boldsymbol{M}_{IP}$ points to the left (right), the adjacent out-of-plane magnetized element $\boldsymbol{M}_{OOP}$ points up (down). This confirms the chiral nature of the DMI; the coupling between the two elements agrees with the expected left handedness arising at the Pt\Co interface. Therefore, the DMI not only has the power to twist magnetic moments at the atomic length scale as demonstrated previously but can also be effective in larger structures where the in-plane and out-of-plane magnetized regions can be represented by a macroscopic magnetic moment $-\boldsymbol{D} \cdot (\boldsymbol{M}_{IP} \times \boldsymbol{M}_{OOP})$.



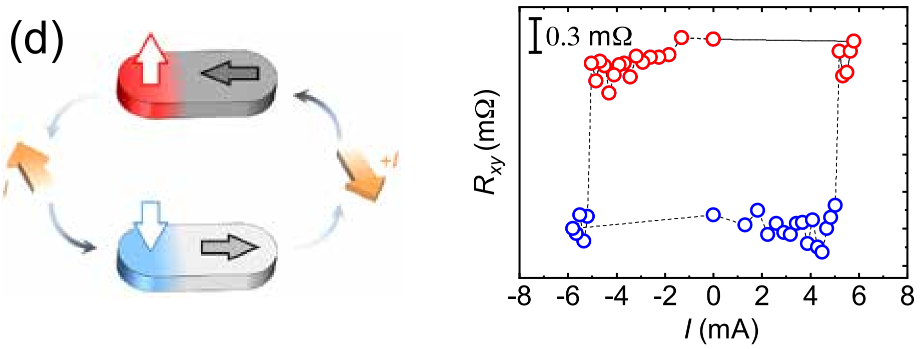


Figure 3: (a) Schematic of a hybrid in-plane/out-of-plane structure fabricated on top of a Pt cross (yellow) designed for anomalous Hall effect measurements. Here the electric current is applied along the short axis of the island and the anomalous Hall effect resistivity R_{xy} is measured transversally. Scale bar: 500 nm.
(b) Anomalous Hall effect resistivity as a function of an out-of-plane magnetic field where the magnetic state of the in-plane magnetized part of the island has been preset by a positive (empty circles) or negative (full circles) in-plane magnetic field. The hysteresis loops are biased due to an effective field arising at the boundary between the out-of-plane and in-plane magnetized parts. (c) Anomalous Hall effect resistivity measured as a function of an in-plane magnetic field reveals simultaneous switching of the out-of-plane magnetization. (d) The magnetic state can be controlled by an electric current whose polarity sets the state. The anomalous Hall effect resistivity measurements as a function of electric current pulse amplitude reveal that the magnetic state can be switched with a current of 5.5 mA, which corresponds to a current density of $J \approx 4.7 \times 10^{11}$ A/m². From [16]. Reprinted with permission from AAAS.

All-electric switching and readout

In order to proceed towards technologically relevant devices where full electric control of the magnetization is essential for next-generation data storage devices, we fabricated hybrid out-of-plane/in-plane magnetized structures on top of Pt cross structures (Fig. 3a), where the state of the out-of-plane magnetized part can be detected electrically. In particular, the anomalous Hall effect is used to detect the *z*-component (i.e. $\boldsymbol{M}_{OOP}$) of the magnetization via the Hall resistivity R_{xy}. Prior to the application of the H_z field, the state of $\boldsymbol{M}_{IP}$ is preset with a positive or negative H_y field, respectively. The DMI effective field localized at the interface between the out-of-plane and in-plane magnetized regions contains an out-of-plane component acting here effectively as an exchange bias. Therefore the positive and negative shift of the hysteresis loops seen in Fig. 3b reflects the fact that the sign of the effective field [5,11,12] is reversed for different initial configurations of the in-plane region. This reveals the power of the chiral coupling: the DMI is strong enough to spontaneously form the chiral states upon releasing the external magnetic fields. Therefore, setting the in-plane magnetization affects the out-of-plane magnetization reversal. In additon, the magnetic state of the out-of-plane magnetized regions can be controlled by the application of the in-plane magnetic field (Fig. 3c).

When an electric current is applied, the Pt underlayer also provides a source of a net spin current generated via the spin Hall effect, which offers a means to manipulate the magnetic state of the structures. It has been previously shown that the magnetic state of in-plane or out-of-plane magnetized magnets can be controlled by spin-orbit torques arising from the interaction between the absorbed spin current and the local current [13,14]. However, to achieve magnetization switching with an electric current, an additional symmetry-breaking is required. This is usually achieved by applying an additional external in-plane magnetic field, which is not desirable for device applications. In our case, the symmetry is intrinsically reduced by the presence of the in-plane magnetized part enabling the deterministic spin-orbit torque-induced switching. The spin-orbit torques thus cause simultaneous switching of the out-of-plane and in-plane regions. These can be switched back and forth by reversing the polarity of the applied electric current. This is demonstrated by the hysteresis loop presented in Fig. 3d and, in order to achieve the field-free current-induced switching, a current density of $J \approx 4.7 \times 10^{11}$ A/m^2 is required. This demonstrated magnetic field-free, all-electrical writing and readout of the magnetic state opens opportunities to design new data storage and memory devices. For example, the lateral chiral coupling can be used to realize magnetic logic devices controlled purely by an electric current [15].

Chiral coupling in complex geometries

Lateral chiral coupling can also be implemented in more complex two-dimensional systems of various geometries. Structures with two out-of-plane magnetized regions (in red) that coupled antiferromagnetically across an in-plane region (in blue) are shown in Fig. 4a. Once the magnetic state of the in-plane region is set, the two out-of-plane elements or-

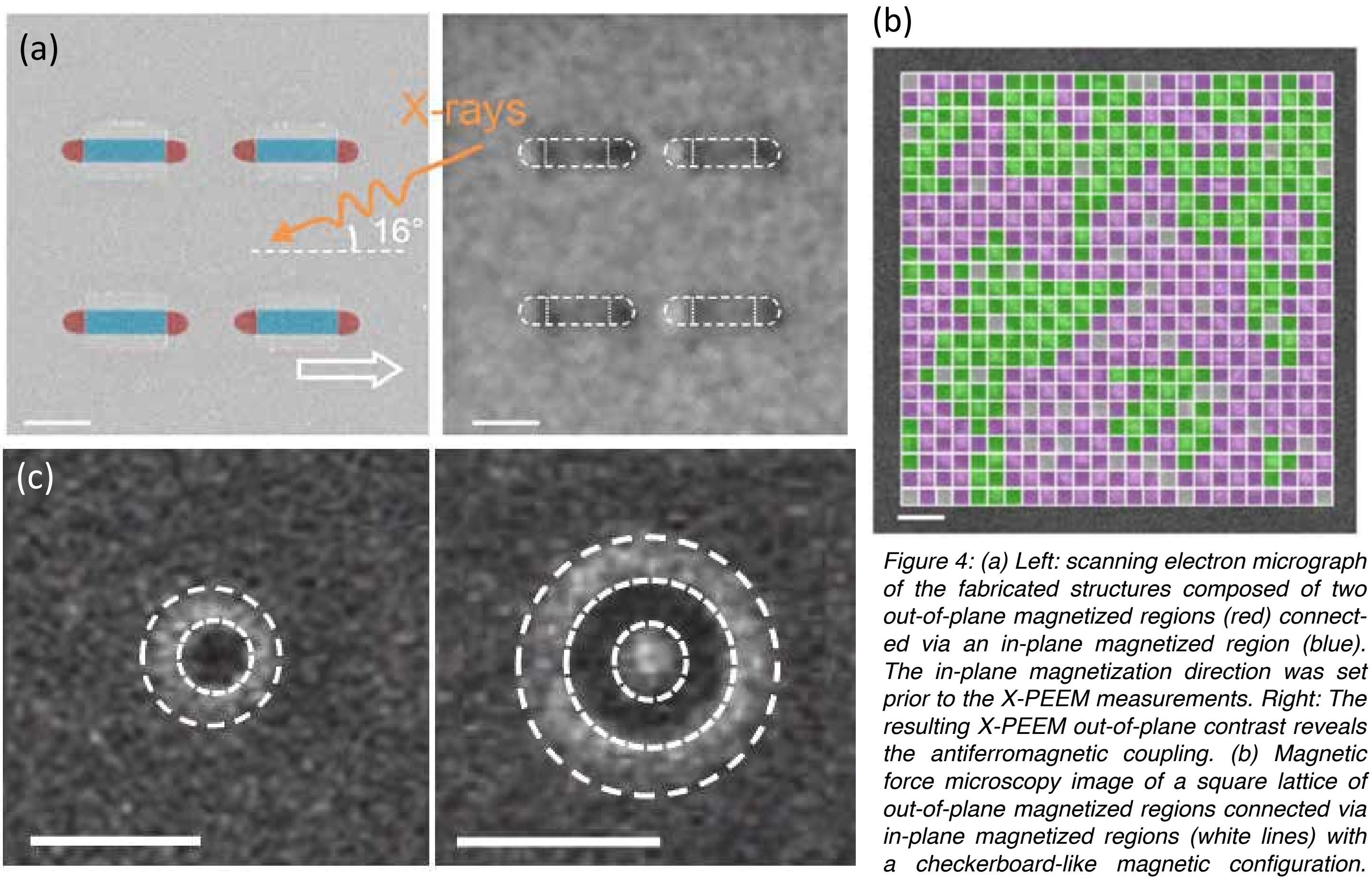


Figure 4: (a) Left: scanning electron micrograph of the fabricated structures composed of two out-of-plane magnetized regions (red) connected via an in-plane magnetized region (blue). The in-plane magnetization direction was set prior to the X-PEEM measurements. Right: The resulting X-PEEM out-of-plane contrast reveals the antiferromagnetic coupling. (b) Magnetic force microscopy image of a square lattice of out-of-plane magnetized regions connected via in-plane magnetized regions (white lines) with a checkerboard-like magnetic configuration. There are two energetically equivalent antiferromagnetic domains highlighted in green and purple. (c) Magnetic force microscopy image of a skyrmion-like magnetic state, which occurs as a result of chiral coupling mediated by in-plane magnetized rings (dashed circles). The topological charge can be altered from ±1 to 0 by adding another out-of-plane ring. All scale bars correspond to 500 nm. From [16]. Reprinted with permission from AAAS.

der in an antiferromagnetic fashion, mimicking the negative atomistic Heisenberg exchange interaction on a mesoscopic scale. Magnetic couplings in vertically layered structures such as exchange bias or Ruderman-Kittel-Kasuya-Yosida coupling play a key role in magnetic data storage devices. However, the magnetic coupling in laterally defined structures has so far been limited to dipolar interactions, which are very small in ultrathin magnetic films currently used in spintronics. The lateral chiral coupling effect, which is effective also on a mesoscopic scale, provides a robust alternative to the systems coupled via dipolar interaction [16].

The lateral antiferromagnetic coupling demonstrated in simple building blocks shown in Fig. 4a can be extended into two dimensions by arranging these blocks into a square lattice. Such a lattice is composed of out-of-plane magnetized squares connected via narrow in-plane magnetized regions mediating the chiral coupling, and provides a mesoscopic analogue to a correlated Ising-like spin system. The resulting checkerboard-like magnetic state, captured by magnetic force microscopy, is shown in Fig. 4b. The alternating dark and bright contrast reflects the fact that the out-of-plane elements are ordered in an antiferromagnetic fashion. Nevertheless, there are two energetically equivalent magnetic configurations (up-down-up-down or down-up-down-up), which results in the formation of two different antiferromagnetic domains highlighted in green and purple. This provides an interesting development in the field of artificial spin systems [17,18].

The concept of chiral coupling can be further implemented in curved geometries as demonstrated by the skyrmion-like structures shown in Fig. 4c, which are composed of different numbers of in-plane magnetized rings (dashed lines). The alternating even and odd number of in-plane rings changes the topological charge of the resulting magnetic texture. For an odd number of in-plane rings, the topological charge is +1 or -1, depending on the orientation of the magnetization of the central region. For an even number of in-plane rings, the topological charge is 0, and the so-called 2π skyrmions are topologically equivalent to a ferromagnetic state, i.e. they can simply be unrolled into a ferromagnetic state.

Although here the lateral coupling has been produced in a controllable way by spatially tailoring the local anisotropies, it may be possible to find similar effects in inhomogeneous magnetic systems with broken inversion symmetry, for example, in magnetic systems near the spin reorientation transition [19] or in multilayer magnetic films [20,21].

Acknowledgments

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Top right picture on the cover page: Paul Scherrer Institute, Markus Fischer

Milestones in Physics (17)

On the Evolution of Black Hole Physics

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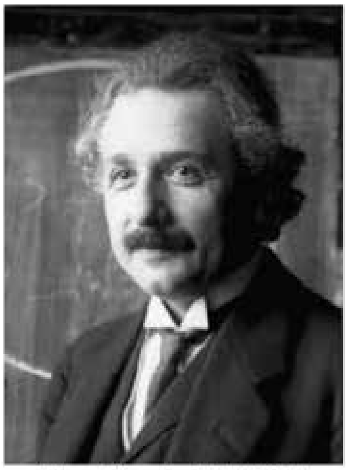
The extended history of black hole physics began with Schwarzschild's surprising discovery of an exact spherically symmetric solution of Einstein's vacuum equations, shortly after Einstein had completed the foundations of general relativity (GR). Because of an apparent singularity of this solution relativists did not fully understand it until after Einstein's death. This is the main reason that the formation of black holes in gravitational collapse was not addressed until the 1960s, apart of one very important exception. In 1939 Oppenheimer and Snyder studied in the framework of GR the relativistic collapse of a spherically symmetric dust cloud and found an exact interior solution of the idealized star that could be matched to the exterior Schwarzschild solution. In their paper they describe crucial aspects of the collapse to a black hole, but because of the apparent Schwarzschild singularity a full understanding came only many years later. The situation changed radically with an amazing chain of important astronomical discoveries in the 1960s and 1970s, and important theoretical work. Despite of these developments, "*many who rejected black holes in the 1970s as conceptually absurd remain hard-core skeptics today*" (W. Israel in 1997). At present this circle has become rather small because of great recent developments in the field as we shall discuss in this article.



Albert Einstein (1879-1955)

Karl Schwarzschild (1873-1916)

Schwarzschild black holes

The solution of Einstein's field equations, which describes the field outside of a spherically symmetric mass distribution, was found by Karl Schwarzschild only two months after Einstein published his field equations. Schwarzschild performed this work under rather unusual conditions. In spring and summer 1915 he was assigned to the eastern front. There he came down with an infectious disease and in the fall of 1915 he returned seriously ill to Germany. He died only a few months later, on May 11, 1916. In this short period of time, he wrote three significant papers, in spite of his illness. One of these dealt with the Stark effect in the Bohr-Sommerfeld theory, and in another he solved Einstein's vacuum field equations for a static, spherically symmetric field. From this solution he derived the precession of the perihelion of Mercury and the bending of light rays near the sun. Einstein had calculated these effects previously by solving the field equations in post-Newtonian approximation.

Einstein was thrilled when he received Schwarzschilds discovery and replied: "*I would not have expected that the exact solution to the problem could be formulated so simply*" [1]. Schwarzschild's solution is analytically indeed very simple:

$$ds^2 = -c^2\left(1-\frac{2m}{r}\right)dt^2 + \frac{dr^2}{1-2m/r} + r^2(d\vartheta^2 + \sin^2\vartheta\, d\varphi^2), \quad (1)$$

where m is at this stage a constant of integration. This metric has an apparent singularity for $r = 2m$. This was alarming for Schwarzschild and Einstein. Since the metric coefficient proportional to dr^2 is only positive for $r > 2m$ they concluded that the solution could only be used there.

It was therefore satisfying for both, when a few weeks later Schwarzschild sent another paper to Einstein from the Russian front on a solution inside the star for a simple model (constant matter density) [2]. The circumference of this extreme compact star turned out to be larger than that of the apparent singularity of his vacuum solution. This seemed to indicate that the disturbing singularity did not exist in the real world.

For the combined solution the constant $2m$ was fixed by the Newtonian limit at large distances:

$$2m = R_S := 2\frac{GM}{c^2} \quad (2)$$

(G is Newton's constant, c the velocity of light and M the mass of the star), soon called the *Schwarzschild radius*. This attitude of Einstein (and others) is reflected, for instance, in a paper in 1939 [6], in which he claimed to provide "*a clear understanding as to why these 'Schwarzschild singularities' do not exist in physical reality.*" His argument was based on a simple spherical cluster model of stars, all of which move on circular orbits. The simple solution of Einstein's field equations showed that when the circumference of the spherical cluster is smaller than 3/2 of the Schwarzschild 'singularity', then the velocity of the outer stars would exceed the speed of light, which is impossible. While the mathematics of the paper is all right, this is no argument against the existence of what we call black holes. It just shows that then no equilibrium is possible for the cluster and it has to collapse.

The apparent Schwarzschild singularity as an event horizon

It took a long time until relativists understood that what was called the Schwarzschild singularity is actually a *coordinate singularity* [1]. Merely Schwarzschild's coordinates fail to

1 It has been almost completely overlooked that Lemaître showed already in 1933 in his important paper [3], Sect 11, that the Schwarzschild singularity is spurious. In his words: **"The singularity of the Schwarzschild field is thus a fictitious singularity"**. He showed this by transforming the standard form of the metric to new coordinates which are defined by a

properly cover the spacetime region where Schwarzschild's radial coordinate r approaches R_S. (This coordinate singularity is similar to the fact that the polar angles of a sphere become useless on the north pole.) The Schwarzschild sphere is nevertheless of crucial physical significance. It turns out – as we shall see – that it is an event horizon, a most important concept of black hole physics.

The original solution (1) can be regularly extended to a larger spacetime, as was most clearly discussed in 1960 in an influential paper by J. B. Kruskal, but other authors also contributed to the new insight. The Kruskal extension, covered by two coordinates u,v, beside the usual two angular coordinates, is *maximal*, which means that every geodesic can either be extended to arbitraryly large values of the affine parameter, or it runs into a real singularity on the surface $v^2 - u^2 = 1$ for a finite value of this parameter. The causal relationships in the Schwarzschild-Kruskal manifold are quite transparent. For instance, any particle which passes through the Schwarzschild sphere must run into a singularity within a finite proper time. No return is possible. Even light will end up there. In this sense the "dangerous" Schwarzschild sphere is an **event horizon**, a kind of one-way membrane.

On the basis of simple calculations, the situation is in all modern text books on GR (for instance in [4] and [5]) described in a figure, known as the *Kruskal-Szekeres diagram*. Part of this is shown for the vacuum field outside a spherically symmetric collapsing star in Fig. 2. The fact that the gravitational field outside the collapsing star is a domain of the Schwarzschild-Kruskal solution is known as the generalized *Birkhoff theorem*. This may not be too surprising, because the electromagnetic field outside a time dependent spherical charge distribution is time-independent, and equal to the Coulomb field of the total charge.

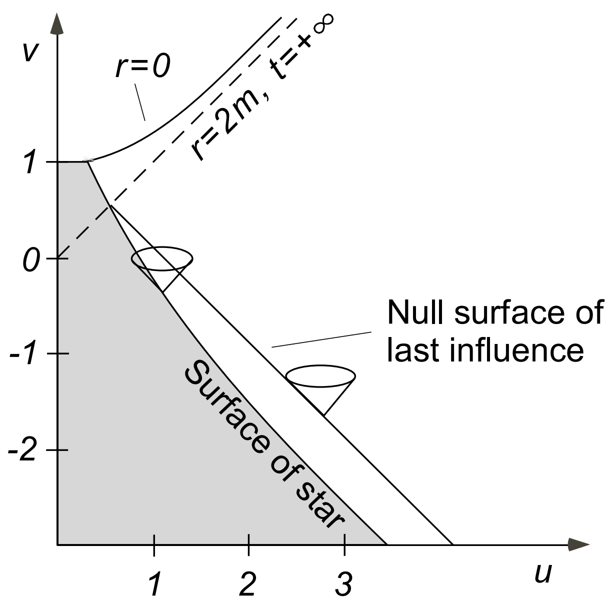


Figure 2: Spherically symmetric collapse in Kruskal coordinates. Behind the dashed horizon the star becomes invisible for a distant observer. (Matching coordinates inside the star are not specified.)

congruence of freely falling test particles in radial directions, that became known in 1964 as *Novikov coordinates*. If Lemaître's insight would have been known, the history of black hole physics would have been different, because the apparent singularity would have soon be understood as an *event horizon*.

Oppenheimer-Snyder collapse

In the same year 1939 of Einstein's argument against black holes, J. Robert Oppenheimer and his student Hartland Snyder (OS) investigated for the first time the gravitational collapse of a simplified stellar model [7]. In spite of the highly idealized collapse scenario, with uniform density and zero pressure (dust), it illustrates many generic features of gravitational collapse and black hole formation, a true milestone. Since the solution is analytic it is simple to work out all aspects and develop a detailed understanding of the problem.

From the generalized Birkhoff theorem we already know the exterior solution. The interior solution of the OS-collapse is given by a metric which is familiar from Friedmann's closed cosmological solution, for which the scale factor $R(\tau)$ satisfies the Friedmann equation, and the density of matter is proportional to $R^{-3}(\tau)$. The dust particles in the star follow radial geodesics for the Friedmann metric and can easily be determined by integration (see Fig. 3). In particular, the motion of the surface is given in parametric form by

$$R = \frac{1}{2} R_0 (1 + \cos\eta), \quad \tau = \left(\frac{R_0^3}{8M}\right)^{1/2} (\eta + \sin\eta), \qquad (3)$$

where τ is the proper time and R_0 the value of the radial area coordinate when the star begins to collapse, and the parameter η varies from 0 to π. Of interest is the proper time at which a shell initially reaches $R = 2M$. One easily finds from (3) for the corresponding η-parameter $\eta_{2M} = \cos^{-1}[(4M/R_0) - 1]$.

More difficult is the question of how the two solutions match. It turns out that a smooth matching can be achieved for zero pressure. This would, for example, not be possible for a uniform nonzero pressure. In that case the infinite pressure gradient at the star's surface would blow off the outer layers of the the star, and would send a rarefaction wave propagating inward toward the center.

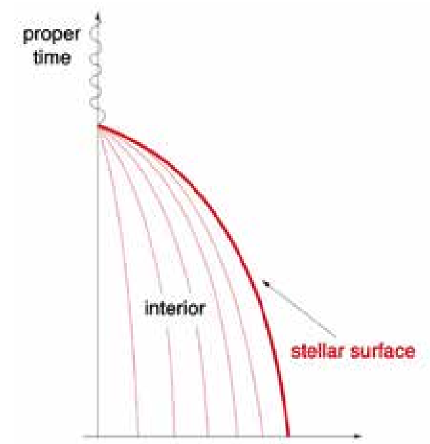


Figure 3: Worldlines of dust shells in the OS-collapse. They all reach the singularity at the same proper time.

Event horizon, trapped surfaces and apparent horizon

For the OS-collapse one can explicitly explain and determine the following concepts. The *event horizon* is by definition formed by the boundary of outgoing light rays that do not reach a distant observer. In our case it is obviously generated by those null rays that intersect the surface of the star just when the surface crosses $R = 2M$ (see Fig. 4). With the explicit knowledge of the interior metric it is easy to determine the event horizon trajectory inside the star, as indicated in Fig. 4. We emphasize at this point that the event horizon is a *global* concept; the entire spacetime has to be known in order to determine its position, which is rarely the case.

For this reason the so-called *apparent horizon*, which is determined from a knowledge of the local spacetime geometry is important. To define it, we first introduce the concept of a *trapped region*, which is the set of all spacetime points for which an outgoing bundle of null rays locally converges, i.e., its cross sectional area instantaneously decreases. The apparent horizon is the outer boundary of the trapped region. One can show that whenever an apparent horizon has been formed, the event horizon of which is on or strictly outside the apparent horizon.

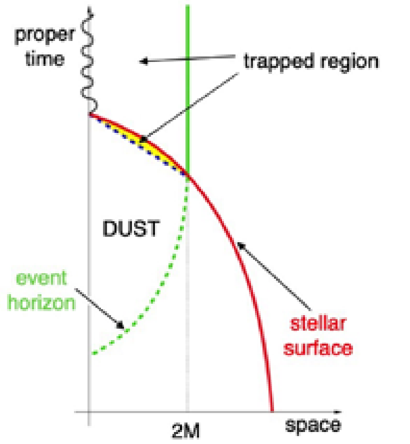


Figure 4: Qualitative evolution of the relevant surfaces in the collapse of a dust sphere. The apparent horizon, which is the outer boundary of the trapped region, appears when the event horizon reaches the surface of the star at the Schwarzschild radius 2M.

For the OS-solution the trapped region is shown in Fig. 4. Note that the apparent horizon first appears at the value η_{2M} given earlier. It stays there and coincides with the event horizon. This is, however, not a generic property. For instance, in the case of a perfect fluid the apparent horizon is produced earlier.

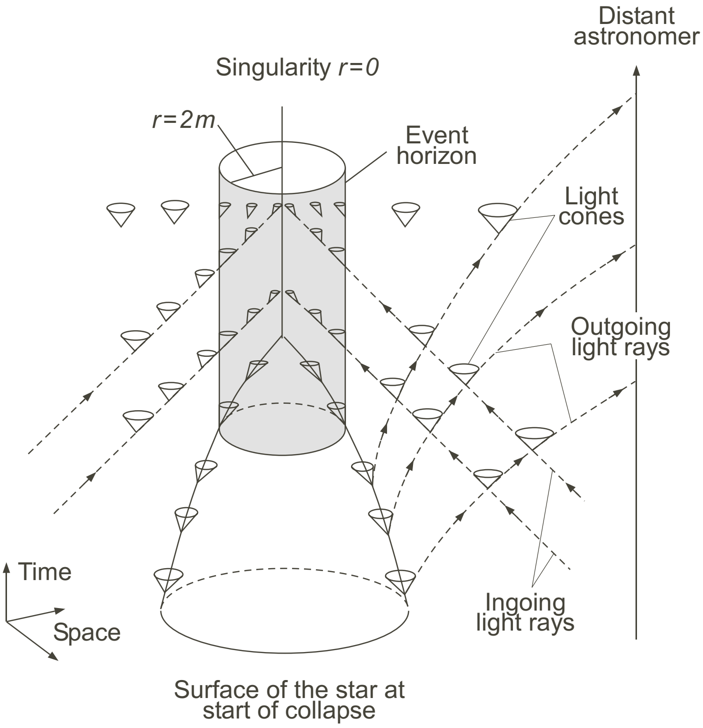


Figure 5: Spacetime diagram of a collapsing star in Eddington-Finkelstein coordinates. (Matching inner coordinates are not specified.)

Spherically symmetric collapse to a black hole

We now describe qualitatively the spherically symmetric, catastrophic collapse of a supercritical mass. Since, according to the generalized Birkhoff Theorem, the exterior field is a region of the Kruskal manifold, the collapse can be visualized in Kruskal coordinates as shown in Fig. 2. In Fig. 5 we show a more detailed picture of the same process in so-called Eddington-Finkelstein coordinates (defined in all GR-textbooks). From these two figures we may draw the following conclusions:

1. Equilibrium is no longer possible when the stellar radius becomes smaller than the radius of the event horizon, since the world lines of the stellar surface must lie inside the light cones. In fact, physical conditions on the equations of state for the collapsing matter imply that the pressure inside the star will diverge already for radii strictly larger than that of the event horizon (see [5], Sect. 7.9.3, Eq. (7.108)). Collapse to a singularity cannot be avoided. At some point in the vicinity of the singularity, GR will probably no longer be valid, since quantum effects will become important. (Unfortunately, we are still far away from a synthesis of GR with quantum theory.)
2. If a signal is emitted from inside the event horizon, it will not reach a distant observer. The stellar matter is literally cut off from the outside world. Also light rays will approach the singularity. Thus, the event horizon is the boundary of the region which is causally connected to a distant observer. It is defined in general by this property. The horizon acts like a one-way membrane through which energy and information can pass to the interior, but not to the exterior. The existence of event horizons, or causal boundaries, in our universe is a remarkable consequence of GR. The singularity is behind the event horizon, and hence has no causal connection to an external observer; he cannot "see" it. It has been conjectured by R. Penrose that this is true for all singularities that arise in consequence of realistic astrophysical collapse scenarios. ("**cosmic censorship hypothesis**").
3. For very large masses the tidal forces at the horizon are harmless. An observer of human size on the surface of a collapsing star will not notice anything peculiar when the horizon is crossed. Thus the horizon is a global phenomenon of the spacetime manifold. Note also the "null surface of last influence" shown in Fig. 2. An external observer who has passed this surface (moving forward in time) is causally decoupled from the star before it plunches through the horizon.
4. An external observer far away from the star will see it reach the horizon only after an infinitely long time. As a result of the gravitational time dilation, the star "freezes" at the Schwarzschild horizon. However, in practice, the star will suddenly become invisible, since the redshift of light emitted by the star will start to increase exponentially, and the luminosity decreases correspondingly. The characteristic time for this to happen is $\tau \sim R_S/c \simeq 10^{-5}(M/M_\odot)$ s; for $M \sim M_\odot$ this is extremely short. Afterwards, we are dealing with a **black hole**. It makes sense to call the horizon the surface of a black hole, and the external geometry the gravitational field of the black hole. The interior is not relevant for astrophysics. When observed from a distance, the exterior field looks exactly like that of any massive object. Its surface area is $4\pi R_S^2$.

For stars with masses larger than about 11 $M_\odot$ nuclear fusion proceeds all the way up to iron. At this point the central core runs into an instability and collapses catastrophically. In more detail the evolution proceeds as follows: In the last stages of nuclear energy generation an "iron core" of burned out elements is formed in the central region, which has the structure of a white dwarf. Around this core of iron-peak elements an onion structure is built up as a result of shell burning in various shells. The central white dwarf-like region finally becomes unstable due to electron capture and/or photo-disintegration of the iron-peak elements into α-particles. At this point the core starts to collapse virtually in free fall. There are now two possibilities.

1. For some mass range, **neutron star** residues with increasing masses of 1.4 – 2.0 $M_\odot$, say, will be left behind a prompt or delayed supernova explosion.
2. For sufficiently massive stars, the core will, however, most likely accrete too much mass to be stable and will then collapse very quickly to a **black hole**. In this picture we do not expect a collapse directly to a black hole. A proto-neutron star is formed first, which accretes sufficient mass through a stalled shock until it becomes unstable and undergoes a general relativistic collapse. It is difficult to say for which mass range of stars this is going to happen, but we do expect the formation of black holes for very massive stars. Even though precise numbers are difficult to estimate there are certainly millions of such stellar mass black holes in our Galaxy.

Realistic collapse calculations became possible with the impressive developments of numerical relativity and by continued increase in computer power. This has become a vast field. For interested readers we recommend the excellent text book [11].

Stationary black holes, uniqueness theorem

> *"In my entire scientific life (. . .) the most shattering experience has been the realization that an exact solution of Einstein's equations of general relativity, discovered by the New Zealand mathematician Roy Kerr, provides the absolutely exact representation of untold numbers of massive black holes that populate the Universe."*
> S. Chandrasekhar (1975)

All stars rotate more or less rapidly. When a horizon is formed during gravitational collapse, a Schwarzschild black hole is thus never produced. One expects, however, that the horizon will quickly settle down to a stationary state as a result of the emission of gravitational waves. The geometry of the stationary black hole is not anymore spherically symmetric.

It is remarkable that we know all stationary black hole solutions of Einstein's vacuum equations. Surprisingly, they are fully characterized by just two parameters, namely the mass and angular momentum of the hole. These quantities can be determined, in principle, by distant observers.

Thus when matter disappears behind a horizon, an exterior observer sees almost nothing of its individual properties. One can no longer say for example how many baryons formed the black hole. A huge amount of information is thus lost. The mass and angular momentum completely determine the external field, which is the celebrated **Kerr solution** of Einstein's vacuum equations. This led J. A. Wheeler to coin the expression "*A black hole has no hair*", and the uniqueness statement is now known as the **no-hair-theorem**.

The proof of this is an outstanding contribution of mathematical physics, and was completed only in the course of a number of years by various authors (W. Israel, B. Carter, S. Hawking and D. Robinson). A first decisive step was made by W. Israel (see [8]), who was able to show that a *static* black hole solution of Einstein's vacuum equation has to be *spherically symmetric* and, therefore, agree with the Schwarzschild solution. For a streamlined very readable text book on the proof of the no-hair-theorem we refer to [16].

We describe now some important properties of the Kerr solution. The gravitational field has a whirling contribution. *Stationary* observers see an unchanging spacetime geometry. Non-rotating, static observers (relative to "the fixed stars") can only exist outside the *static limit* shown in Fig. 6. What is technically called a Killing horizon in this figure is an *event horizon*. Within the so-called ergosphere nothing can prevent a rocket (with any power) from rotating about the black hole.

Visualizing the spacetime geometry is made easier by considering the structure of light cones. We examine this more closely in the equatorial plane, as indicated in Fig. 7. Each point in this plane represents an stationary moving light source. The light signals which have formed shortly after being emitted from the marked points are shown as circles in this figure. We note the following facts:

a) Since the four-vector k of stationary orbits is *timelike* outside the static limit, the points of emission are inside the wave fronts.
b) At the static limit k becomes *lightlike*, and the point of emission lies thus on the wave front.
c) Inside the ergosphere k is *spacelike* and hence the emitting points are outside the wave fronts.

Ergoregion and the Penrose process

Since k is spacelike inside the ergosphere, it is possible in principle to extract energy from a black hole, thereby reducing its angular velocity and thus also the size of the ergosphere. Imagine, as a gedankenexperiment, a piece of matter which falls freely from a large distance into the ergosphere, where it breaks up into two fragments, in such a way that the first one falls inwards through the horizon. The

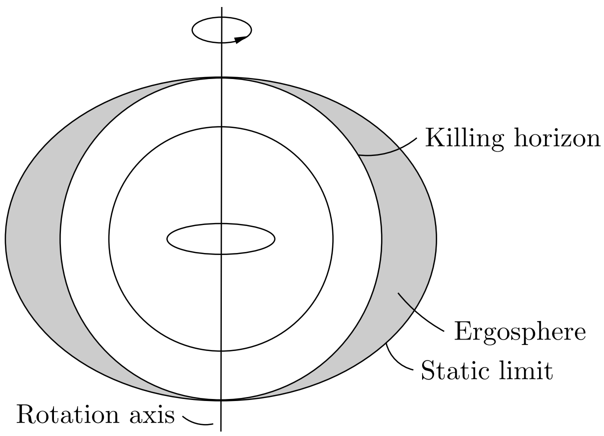


Figure 6: Cross section through the axis of rotation of a Kerr solution.

second fragment can leave the ergosphere and carry away more energy than the incoming object had.

This process, called **Penrose mechanism**, could provide simultaneously permanent solutions to our energy and waste disposal problems. In this simple version it plays no role in astrophysics. There are, however, generalized Penrose processes in which the ergosphere plays also a central role, but involve magneto-hydrodynamic flows of accreting matter. Numerical simulations in recent years have shown that in these relativistic jets are naturally formed. For a review and literature see, e.g., [9].

Black holes with hair

The uniqueness theorem discussed earlier extends to the coupled Einstein-Maxwell system. For this the stationary black holes, described by the Kerr-Newman solution, are characterized by three parameters, namely the two of the Kerr solution plus the electric charge. On the basis of past experience and intuition it was generally believed that this uniqueness theorem should have a natural generalization to the non-Abelian case, namely that the structure of such black holes should be determined uniquely by the hole's mass, intrinsic angular momentum and the global Yang-Mills (YM) charges defined at spatial infinity. It came, therefore, as a surprise when "colored black holes" were discovered in 1989 by three groups [12], because they represent counter examples to the "no hair conjecture " just spelled out. Indeed, these colored black hole solutions are static, spherically symmetric and have vanishing YM charges. Asymptotically they approach the Schwarzschild solution, but they have "Yang-Mills hair".

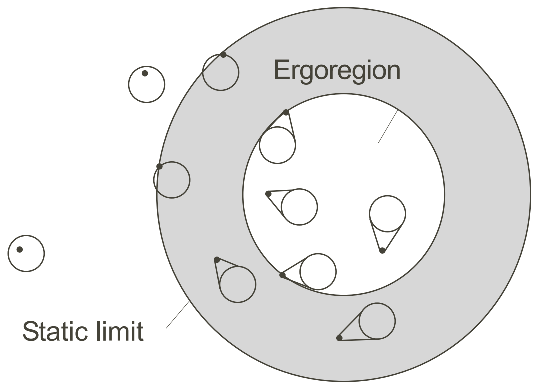


Figure 7: Structure of light cones of a Kerr black hole in the equatorial plane.

Together with Z.-H. Zhou, a Chinese post-doc at the time, we showed soon afterwards, that these colored black holes are unstable [13]. Because of this instability we then searched for black holes of other nonlinear matter models which would provide counter examples to the generalized no hair conjecture, but in addition would be stable. As an interesting example we discovered that the Einstein-Skyrme system has – for a certain range of coupling constants – indeed such black holes [14] that are also stable [15]. After this several members of our group in the Institute of Theoretical Physics at Zürich University (O. Brodbeck, S. Droz, M. Heusler, G. Lavrelashvili, M. S. Volkov and I) worked for several years in varying combinations on related problems, and encountered a number of surprises. Our contributions are discussed by M. Heusler in a long invited article for the *Living Reviews* of the Albert Einstein Institute in Potsdam [16]. (Together with two other authors this was updated in 2012.) Another extended article appeared in *Physics Reports* by M. S. Volkov and D. V. Gal'tsov [17]. After our research group dissolved shortly before my retirement, Michael Volkov was the only one who pursued this field of research.

Unfortunately, non of the discovered solitons and black holes is presumably of physical relevance. Nevertheless, we enjoyed the work, also from a mathematical point of view.

The four laws of black hole dynamics

In principle it is possible to extract an enormous amount of energy from a rotating black hole, thereby reducing its angular velocity and thus also the size of the ergosphere. The fraction of rotational energy that can ideally be extracted is limited by what is called the **second law of black hole dynamics**, which implies that the surface of a black hole cannot decrease. The general form of this **area law**, formulated later in this section, is in close formal analogy with the second law of thermodynamics. Not only the second law, but also the other main laws of thermodynamics have close analogies in the physics of black holes.

While the formal analogy between these two sets of laws has been established very early (~ 1973), the question of whether there is deep physical reason behind this, is still a matter of debate. A first important step in this direction was made by S. Hawking's discovery of thermal radiation by black holes in a semi-classical approach (quantized matter fields on a classical black hole background). In this section we give only an introduction to the classical aspects of the subject.

The analogue of the **zeroth law** of thermodynamics – the constancy of the (absolute) temperature T throughout a body in thermal equilibrium – is the constancy of the so-called *surface gravity*, usually denoted by κ, over the horizon of a stationary black hole. For the definition of the surface gravity one considers the 4-vector a of acceleration of a stationary observer and its magnitude $\langle a, a\rangle$. The latter diverges at the horizon, but for a suitable renormalization one obtains a finite limit. (A precise definition is given in my GR-book.) For a Schwarzschild black hole

$$\kappa = \frac{GM}{R_S^2}.$$

In thermodynamics the differential of the internal energy U of a system in thermodynamic equilibrium is given by

$$dU = T\,dS + \alpha, \qquad (4)$$

where α is the differential 1-form of the reversible work. A typical example for α is, in standard notation,

$$\alpha = -p\,dV + \mu\,dN + \ldots. \qquad (5)$$

The combination of these two equations is often called the first law, although an important part of the second law of thermodynamics is also integrated (otherwise we cannot speak of entropy).

In black hole physics, the analogue of the thermodynamic potential $U(S, V, N, \ldots)$ is the total mass as a function of the surface area $\mathcal{A}$ of the horizon, the angular momentum J, the electric charge Q and perhaps other quantities for certain matter models. That $\mathcal{A}$ is the "right" choice will become clear below. For the special case of the Kerr-Newman family one finds by explicit calculation the remarkable formula for the differential of M, the so-called **first law**:

$$dM = \frac{1}{8\pi}\kappa\, d\mathcal{A} + \Omega_H dJ + \phi_H dQ, \qquad (6)$$

where ϕ_H is the constant electric potential on the horizon. (A similar formula holds more generally (see [5], Sect. 8.6.7), not only for the Kerr-Newman black holes.) The analogy with

$$dU = T\,dS - p\,dV + \mu\, dN + \ldots$$

is striking. This suggests the correspondence $T \longleftrightarrow \kappa$ and $S \longleftrightarrow \mathcal{A}$. Within the classical framework proportionality factors are undetermined. Hawking radiation suggests that one should associate a temperature and an entropy to a black hole given by

$$T_H = \frac{\hbar\kappa}{2\pi k_B c}, \quad S = \frac{k_B \mathcal{A}}{4G\hbar}, \qquad (7)$$

where k_B is Boltzmann's constant. The quantity S is the so-called **Bekenstein-Hawking entropy** and T_H the **Hawking temperature**. For this subject we have to refer to the literature. For a Schwarzschild black hole

$$T_H = \frac{\hbar c^3}{8\pi k_B GM} = 6.17 \times 10^{-8} \frac{M_\odot}{M} K, \; S \approx 10^{77} k_B (M/M_\odot)^2.$$

The most general form of the **second law** is due to Hawking. It states the following:

In any (classical) interaction of matter and radiation with black holes, the total surface area of the boundaries of these holes (as formed by their horizons) can never decrease.

The limitation to classical interactions means that we do not consider changes in the quantum theory of matter due to the presence of the strong external gravitational fields of black holes. For macroscopic black holes, this is completely justified. If "mini-holes" were to exist, quantum effects, such as spontaneous (Hawking) radiation, would become important.

As a special example, the second law implies that if two black holes collide and coalesce to a single black hole, then the surface area of the resulting black hole is larger than the sum of the surface of the event horizons of the two original black holes. If this is applied to the coalescence of two Kerr black holes one finds that, in principle, a lot of energy can be released as gravitational radiation.

For comments on the *third law* we refer again to [5], Sect. 8.6.

It should be stressed that within classical theory the correspondence $T \longleftrightarrow \kappa$ should be regarded as formal, since the physical temperature of a black hole is zero. The situation changes radically in quantum theory, where the physical temperature is the Hawking temperature $T_H = \dfrac{\hbar\kappa}{2\pi k_B c}$.

Observational evidence for black holes

The evidence for black holes in some X-ray binary systems and for super-massive black holes in galactic centers is still indirect, but has finally become overwhelming. There is so far, however, little evidence that these collapsed objects are described by the Kerr metric.

In 1964, long before the X-ray window was really opened by the famous satellite UHURU, Y. B. Zel'dovich first suggested the possibility that black holes may manifest themselves as compact X-ray sources in close binary systems. Cygnus X-1, for a long time the solitary example of a black hole candidate with firm supporting evidence, was located by UHURU within a few minutes of arc. By 1971 Cygnus X-1 was linked with a variable radio source which was then more accurately pin-pointed by radio astronomers in Green Bank and Holland. It was finally identified with the single-line spectroscopic binary HDE 226868 by L. Webster, P. Murdin and C. T. Bolton. Using a large body of observational data, D. R. Gies and Bolton [18] derived a lower bound for the mass of the invisible massive compact companion of 7 $M_\odot$, with a preferred value of 16 $M_\odot$.

In December 1982, evidence of a massive invisible component in the extragalactic LMC X-3 was found [19]. In 1985, a third black hole candidate, A0620-00, was identified [20].

To rule out the possibility that the compact companion of mass M_X in a binary system is a neutron star, it is necessary to show that M_X is clearly above about 3 $M_\odot$, an upper limit of neutron star masses. For this it is necessary to establish a large but safe lower limit for M_X. A very useful tool for this is the *optical mass function* of the binary system, consisting of the compact object and a visible star of mass M_{opt}:

$$f(M_X, M_{opt}, i) = \frac{(M_X \sin i)^3}{(M_X + M_{opt})^2}, \qquad (8)$$

where i is the inclination angle of the orbit. Using Kepler's third law we obtain alternatively

$$f(M_X, M_{opt}, i) = \frac{4\pi^2}{GP_b^2}(a_{opt} \sin i)^3. \qquad (9)$$

Here $a_{opt} \sin i$ is the projected semi-major axis of the visible companion. The radial velocity along the line of sight varies periodically with an amplitude (often called K)

$$V_{opt} = \frac{2\pi}{P_b}\frac{a_{opt} \sin i}{\sqrt{1-e^2}}, \qquad (10)$$

where e is the eccentricity of the orbit. Inserting this gives

$$f(M_X, M_{opt}, i) = \frac{P_b}{2\pi G}(1-e^2)^{3/2} V_{opt}^3. \qquad (11)$$

Except for the eccentricity, the right-hand side contains only directly measurable quantities. The radial velocity curve allows one to determine also e. So $f(M_X, M_{opt}, i)$ is observable, and this provides a *lower limit* for the mass M_X:

$$M_X \geq f(M_X, M_{opt}, i). \qquad (12)$$

The main observational uncertainty comes from the radial velocity amplitude V_{opt}, which can be affected by X-ray heating, tidal distortion, non-synchronous rotation of the companion, and spectral contamination due to the surrounding gas and disk.

If this lower limit is not good enough it may be possible to infer a (conservative) lower limit from additional information, for instance when no prominent X-ray eclipses are observed. However, this introduces as a rule considerable uncertainties.

At the time of writing more than a dozen X-ray nova with reliable measurements of the mass function, have been found with $f \geq 3$ $M_\odot$.

Several soft X-ray transients are now known with a mass function larger than 6 $M_\odot$, greatly exceeding the maximum mass of (even rapidly rotating) neutron stars.

Supermassive black holes Sgr A* near the center of the Milky Way and M87* in the giant elliptical galaxy Messier M87

For a long time the best one could say about the evidence of *super-massive black holes* in the centers of some galaxies, was that it was compelling if dynamical studies and observations of active galactic nuclei were taken together. In the meantime the situation has improved radically. Most compelling is the established dark mass concentration of about 6×10^6 $M_\odot$ near the center of the Milky Way (Sg A*), whose extension is less than 17 light hours (see [21]). The least exotic interpretation of this dense dark mass concentration is that it is a super-massive black hole. In Fig. 8 we show the orbit of the star S2 near the centre massive black hole, for which the gravitational redshift has recently been detected.

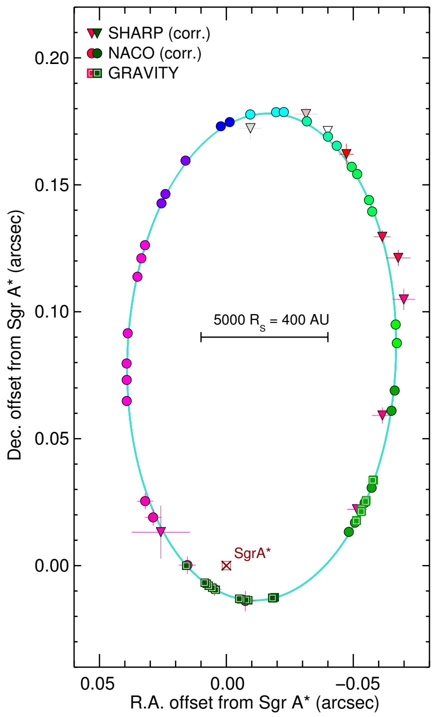


Figure 8: Projected orbit of the star S2 on the sky relative to the position of the compact radio source Srg A. From [23].

On April 10, 2019, the world learned that observations with a world wide array of radio telescopes (called *Event Horizon Telescope*) has generated horizon-scale images near M87*, and established an almost spherical shadow around this supermassive black hole with a diameter of $\simeq 42 \pm 3\ \mu as$ [27]. This is really a milestone in black hole physics. The exact form of the boundary of the shadow is not yet well determined, but significant improvements in the coming years are expected. It is of great interest to test the exact form predicted on the basis of the Kerr solution [2].

It is easy to understand the shadow of Schwarzschild black holes. (For rotating Kerr black holes this is considerably more involved.) The radial equation of null-geodesics is derived in all text books on GR. It can be written in the form

$$\dot{r}^2 + V(r) = \frac{1}{b^2},\quad V(r) = \frac{1}{r^2} - \frac{R_S}{r^3}, \qquad (13)$$

where a dot denotes the derivative with respect to an affine parameter. This looks like the energy conservation for a particle in the potential $V(r)$ with "energy" $1/b^2$. The form of $V(r)$ is shown in Fig. 9. Its maximum is at Schwarzschild's radial coordinate $r = (3/2)R_S$, with

$$V_{max} = \frac{4}{27 R_S^2}.$$

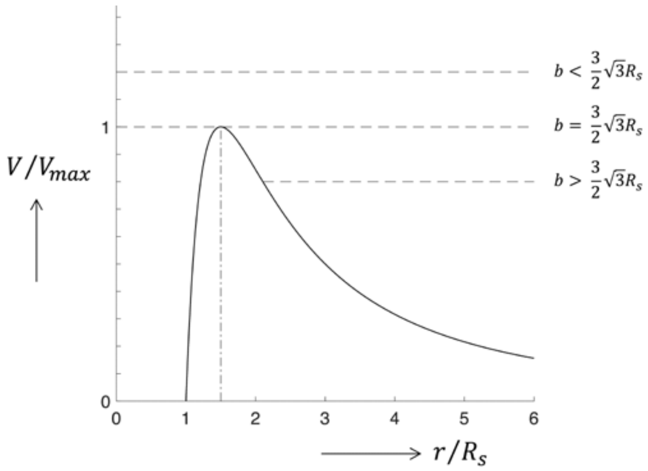


Figure 9: Effective potential for radial motion of light.

This analogy helps to understand the qualitative behavior of null rays as a function of the impact parameter b. For $b = (3/2)R_S$ the orbit of the light ray is an *unstable* circular motion with radial coordinate $r = 3\ R_S/2$ (where R_S is the Schwarzschild radius), often called the "photon ring". For all impact parameters $b < \sqrt{3} \cdot (3/2) R_S = 2.6 R_S$ the incoming photons disappear inside the horizon at R_S. For the converse case $b > \sqrt{3} \cdot (3/2) R_S$ they reach a minimal radial $r > (3/2)R_S$ (turning point in Fig. 9) and return to the asymptotic region. Thus the boundary of the shadow is a circle of radial coordinate $\sqrt{3} \cdot (3/2) R_S \simeq 2.6 R_S$ (circumference

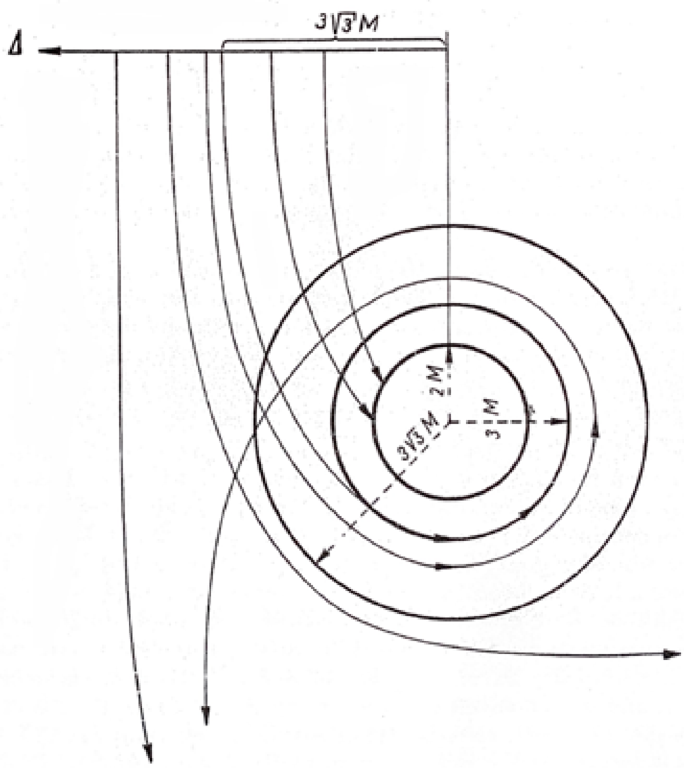


Figure 10: Orbits in the equatorial plane, demonstrating the instability of the unique circular orbit at $r = (3/2)\ R_S$ with impact parameter $b = \sqrt{3} \cdot (3/2) R_S$. (Figure taken from the classic book by von Laue; the impact parameter is denoted by Δ, and the units are chosen with G = c = 1, so $R_S = 2M$.)

2 The distance to the galaxy Messier 87 near the center of the Virgo cluster is 55 million light years. With the present observations the derived mass of the black hole M87* is 6.5 × 10^9 $M_\odot$.

16.3 R_S). The equation of motion for φ is $r^2\dot{\varphi} = 1$, leading to the spiral motions shown in Fig.10 [3].

For the Kerr metric the shadow is, except for a special orientation, no more circular but nearly so; deviations are not larger than about 4 %.

In [27] of the EHT collaboration model images from numerical simulations are presented. It is interesting to see what happens when general relativistic magneto-hydrodynamic GRMHD) simulations of magnetized accretion flows onto black holes are processed on the same basis as the observations. Fig. 11 shows an example of a synthetic image [4].

Coalescence of binary black holes and the emission of gravitational waves

We begin with a few qualitative remarks on the notion of a gravitational wave. This is an idealized approximate concept, as is the case for wave phenomena in other fields of physics. By *gravitational waves* we mean propagating ripples in curvature on scales much smaller than the characteristic scales of the background spacetime. A typical example is the time dependent field due to an aspheric core collapse of a massive star. This produces outgoing fluctuations in the gravitational field outside the star (supernova) on a background which is approximately described by the Schwarzschild metric. A good analogy to this are water waves as small ripples rolling on the ocean's surface with its large scale curvature. Clearly, the separation into ripples and background cannot be precise, but nearly so, because of the widely different length scales involved.

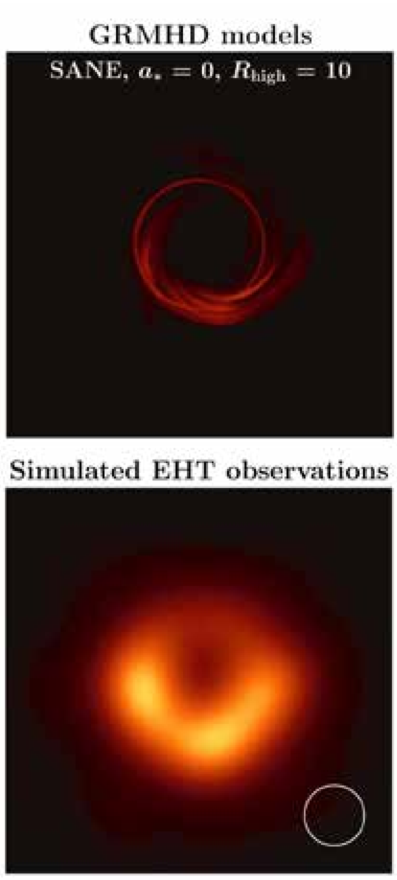


Figure 11: Example of an GRMHD simulation and its procession to an image. The circle indicates the angular resolution of EHT. (From Fig. 4 in [27]).

Close binary systems of stars are particularly interesting sources of gravitational waves. According to GR, the orbit of such a system decreases due to the loss of energy and angular momentum carried away by gravitational radiation. This was shown with high precision radio observations of a binary pulsar by Hulse and Taylor, which confirmed that the losses occur at the rates predicted by GR (Nobel Prize in 1993).

On 11 February 2016 the long expected detection of gravitational waves was announced [22]. A few month earlier, on 14 September 2015 the two LIGO detectors simultaneously observed a transient gravitational wave signal. An extended analysis of the recorded strain led to the conclusion that this is due to the merger of two black holes with masses of about 36 and 29 solar masses, which formed a single black hole of 62 solar masses. The difference (36 + 29) - 62 = 3 solar masses was emitted as gravitational radiation. This discovery plus three other similar events, where the last one was also detected by VIRGO (located nearby Pisa) was the beginning of a new era. For the results published in the original papers, I refer to the article by Philippe Jetzer in the *SPG Mitteilungen* Nr. 53, November 2017, p. 30.

An understanding of how binary black holes coalesce and the derivation of theoretical gravitational wave-form templates was crucial for the analysis of the data. The early phase can be determined analytically with post-Newtonian expansions in *v*/*c*, where *v* is the black hole speed and *c* the velocity of light. (Actually, even the lowest order that is usually treated in GR-lectures works quite well). But the late inspiral phase – as well as the plunge and merger phase – require numerical simulations. This has proven to be very challenging for reasons we cannot discuss here, apart from the problem of coping with a vast dynamical range: Beside solving the highly non-linear Einstein vacuum equations in the rapidly changing strong-field region near the holes, the small perturbations on the background field must be extracted in the far-field region. The solution of these and related problems was an outstanding achievement, by now described in text books on numerical relativity (for interested reader I recommend [11]). Fig. 12 shows a typical numerical simulation and the comparison with a post-Newtonian result, taken from [25]. Existing and future observations will show whether GR is compatible with the details of phenomena so vastly removed from the physical observations on which the theory was founded.

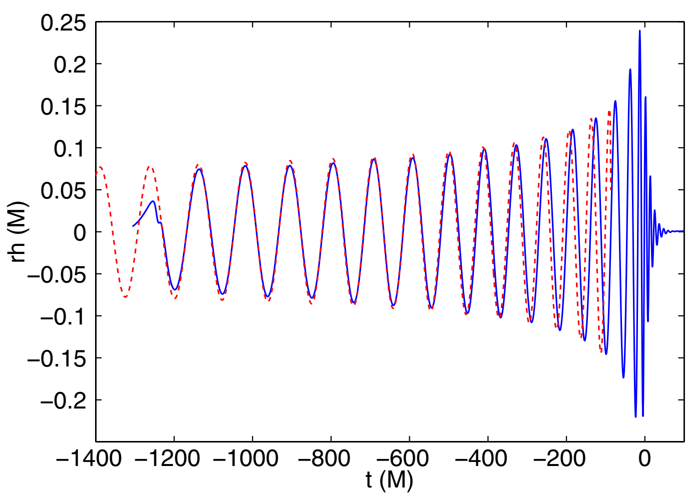


Figure 12: Gravitational strain waveforms from the merger of equal-mass Schwarzschild black holes. The solid curve is the waveform from a numerical simulation, and the dashed curve is a post-Newtonian waveform. Time t = 0 is the moment of peak radiation amplitude in the simulation. From [26].

3 Radiation of hot infalling plasma from the neighborhood of the black hole (accretion disk) that is emitted inside the shadow region can partially escape (within a cone around the radial direction that becomes increasingly narrow for r → R_S), but with such high gravitational redshifts that the shadow appears black. (A special case is the example of radially emitted light signals from a source close to a black hole to a distant observer [5], Sect.4.7.5.)

4 The appearance of a Schwarzschild black hole embedded in a geometrically thin, optically thick accretion disk for a distant observer was first investigated by P. Luminet in 1979 [24].

I conclude with speculative remarks about the possible existence of *primordial black holes*. If primordial perturbations during a very early radiation dominated phase of the universe were sufficiently large some of them would have collapsed under their own gravity, forming black holes. This idea was first introduced by Zel'dovich and Novikov in 1966, and has in recent years been studied in detail. There is the possibility that at least a fraction of the mysterious Dark Matter is composed of primordial black holes. The most straightforward way to distinguish between stellar and primordial origins of binary black hole mergers is to detect one involving a black hole with a mass smaller than the Chandrasekhar limit of 1.4 $M_\odot$. Perhaps this will become possible with the advanced LIGO-VIRGO detectors. This would obviously be of great interest.

Final remarks

Black holes belong to the most fascinating objects physicists have encountered, initially mainly in theory after GR was developed. Decades later it became increasingly clear that they play a central, often dominant role in the real universe. Recently, astronomers were even able to take first photos from a very massive black hole near the center of the giant galaxy Messier M87. Taken all together, most astrophysicists do not worry anymore about possible remaining doubts concerning the existence of black holes. The evidence for (stellar and super-massive) black holes is now so overwhelming that we can pass the burden of proof against them to the few remaining hard-core skeptics.

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Kurzmitteilungen - Short Communications

A hand like no other - When neutrons are good for archeology

Made of bronze and gold 3'500 years ago - but how exactly was it made? Two amateur archaeologists dug it up in the fall of 2017 in the Bernese Jura. Researchers now examine this bronze sculpture at PSI's SINQ neutron source to find answers together with restorers. This will enable conservators to get a unique view into the interior of the sensational find and gain insights into how it was made. Worldwide, there are only around a dozen facilities where neutron radiography can be conducted.

More information: https://www.psi.ch/en/media/our-research/a-hand-like-no-other

Bronze Hand at PSI. Photo: Archaeological Service of the Canton of Berne / Philippe Joner

Applied Machine Learning Days
EPFL Lausanne, 27 - 29 January 2020

For the first time "AI & Physics" is part of the Applied Machine Learning Days as a separate full-day track. If you have some interesting research, a practical project, an awesome product, a promising startup, a sharp expertise, a strong opinion or anything worth sharing and discussing with other researchers, practitioners, fields experts or machine learning and AI enthusiasts, we encourage you to submit a proposal for one of the tracks in development. You can propose a presentation and/or a poster.
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Milestones in Physics (18)

High T_c Superfluidity in a Crystalline Surrounding

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Abstract

The highest T_c in superfluidity was until recently 2.17 K in normal ^{4}He. One of the characteristics of superfluidity is a nearly infinite conductivity of heat. We measured in a specific rare earth compound, $TmSe_{0.45}Te_{0.55}$ single crystals, the onset of superfluidity at 20 K by means of heat conductivity under pressure. In these crystals an incredible amount of excitons with $n_{ex} = 3.9 \cdot 10^{21}/cm^3$ can be permanently created which condense into a Bose liquid. These excitons have a large hole mass of about 50 m_e and couple to phonons, thus are really polarons, which are nearly local modes because of the heavy mass. The phonon dispersion is thus very unusual and the specific heat has been measured at high pressures. The crystals become extremely hard with the condensed excitons, harder than diamond. The compressibility has also been measured.

Introduction

In classical rare earth compounds the 4f state is only partially filled with electrons and this inner atomic state is strictly localized. More outside in ions or atoms are broad bands like 5d and 6s. If the uppermost electronic state is a localized 4f state and the lowest empty band state is a 5d band an exciton can be created by shining a light beam on the compound with enough energy to transfer a 4f electron into the 5d band. The Coulomb attraction between the 4f hole and 5d electron will lower the 5d electron just below the bottom of the 5d band. But since the hole in the 4f state is localized the whole exciton remains localized and is not mobile.

However, if the localized 4f state can be transformed into a narrow band, the exciton becomes mobile, but not resulting in an electric current, since the exciton is a bound electron-hole pair.

In Fig. 1 we show the electronic structure of 3 Thulium mono-chalcogenides, TmS, TmSe and TmTe, with different anion radii, different lattice parameter and thus different crystal field splitting of 5d bands into t_{2g} and e_g sub-bands. This electronic structure is a result of XPS (X-ray Photo-electron Spectroscopy) measuring the occupied electronic states and BIS (Bremsstrahlung Isochromat Spectroscopy) [1] measuring the empty electronic states. $Tm^{3+}S^{2-} + e^-$ is a trivalent metal with one free electron in the 5d conduction band. The occupied $4f^{12}$ level is about 6.5 eV below the Fermi energy E_F and the empty $4f^{13}$ is little above E_F. $Tm^{2+}Te^{2-}$ on the other hand is a divalent semiconductor with an occupied $4f^{13}$ level 0.3 eV (300 meV) below the bottom of an empty 5d band. TmSe with an intermediate anion radius between sulfide and telluride has such a crystal field splitting of the 5d band that the bottom of this band overlaps with the $4f^{13}$ level. This f-d hybridization on the one hand leads to some d-character of the f state and as a consequence to a narrow f-band and on the other hand to some f-character of the bottom of the d-band. It has been conventional to describe the new hybridized f-state as $4f^{13}$-$4f^{12}5d$, consisting of a quantum mechanically mixed state [2]. This phenomenon is named intermediate valence, since the valence of rare earth ions is defined by the occupation of the f-state and thus, TmSe has a valence between 3^+ and 2^+, in fact 2.85^+. This can only be achieved if the 4f state is a narrow band, which is partially filled with electrons [2].

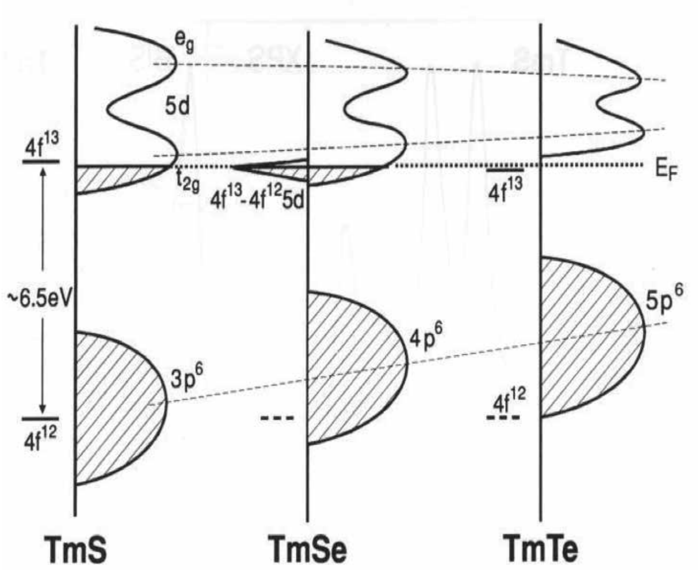


Figure 1. Electronic structure and density of states of the Tm chalcogenides, normalized to the Fermi level E_F

Material Tailoring

One can now make mixtures between the semiconducting TmTe and the metallic intermediate valence TmSe. These mixtures will have a smaller lattice constant than TmTe alone and thus the crystal field split 5d band becomes wider and the gap $4f^{13}$ –bottom 5d band becomes smaller. Thus one can tune the energy gap ΔE between 300 meV and zero (metal) [2,3]. Semiconducting $TmSe_{1-x}Te_x$ single crystals have been grown with x = 0.40, 0.55, 0.68, corresponding to ΔE of 40 meV, 110-120 meV and 170 meV. For these compositions the f state is so close to the 5d band that appreciable hybridization occurs between the tails of the wave functions and the originally localized f-sate will become a narrow band with a width of some tens of meV. Now 4f-5d excitons, with the exciton level in the small gaps, will be mobile because the hole in the narrow 4f band is mobile. Since the f-band is very narrow the effective mass of the hole, and thus of the exciton, is $m_h \approx 50\ m_e$. These excitons have a low concentration at low temperatures because thermal excitation into the excitonic state is rare. Complete measurements have been performed only on $TmSe_{0.45}Te_{0.55}$, therefore we concentrate on this composition.

By optical reflectivity measurements between 6 eV and 1 meV, also at 6 K, we measured a static dielectric constant of ε = 34 and a gap ΔE = 120 meV in agreement with electrical measurements [3, 4, 5]. Also the binding energy $E_B \approx 60$ meV for the excitons could be obtained from the optical measurements [4]

The electronic dispersion in the fcc rocksalt crystal structure shows that the narrow $4f^{13}$ band has a maximum at the Γ point of the Brillouin zone and a minimum at the X point as in Fig. 2. The 5d band dispersion has its minimum also at the X point. An optical transition between the maximum of the 4f and the minimum of 5d band would be an indirect transition and requires maximal the assistance of a Γ - X phonon for k conservation (black curve in Fig. 2).

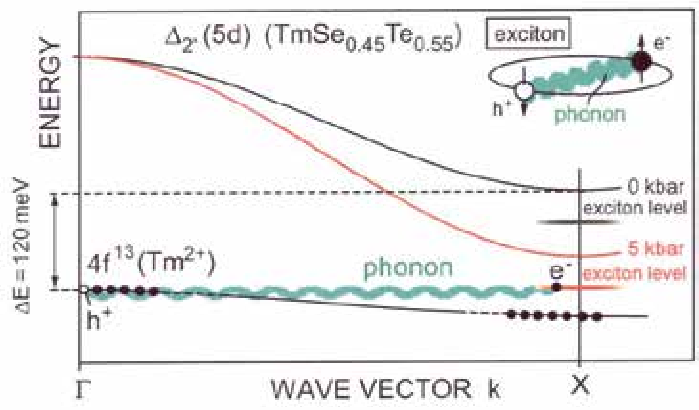


Figure 2. Schematic band structure of $TmSe_{0.44}Te_{0.55}$. Due to 4f-5d hybridization the $4f^{13}$-state becomes a narrow band and has a dispersion. The exciton level with binding energy EB is indicated below the bottom of the 5d conduction band (black curve) The red curve represents the band structure at 5 kbar with the exciton level at X at the same height as the 4f level at Γ. In green is the Γ-X phonon [6]

Creation of Excitons

Under hydrostatic pressure the bottom of the 5d band at X with its exciton level will be lowered with respect to its center of gravity ($5dt_{2g}$-$5de_g$) and shown for 5 kbar the exciton level is exactly at the energy of the 4f-state at Γ (red curve). Now the highest energy electrons in the $4f^{13}$ -band can spill without energy loss into the excitonic state at X leaving behind a positive hole. This transition needs the emission or absorption of Γ – X phonons, which couple to the excitons. So in fact we are dealing with an exciton-polaron. With higher pressure the bottom of the 5d band at X will approach the energy of the $4f^{13}$ -state at Γ and the 4f electrons will enter directly the 5d band and perform a first order semiconductor – metal transition.

In Fig. 3 these transitions can be observed directly with resistivity in the isotherms versus pressure for $TmSe_{0.45}Te_{0.55}$. We look at first at room temperature (300 K) and find a classical pressure dependence of a resistivity, namely the resistivity of a semiconductor decreases with increasing pressure, because the energy gap ΔE decreases with pressure and bands widen and finally the metallic state is achieved (above 11 kbar). Starting with about 5 kbar and best observed at 5 K the resistivity now increases by about 3 orders of magnitude with pressure. This is in contrast with expectations. But it is exactly the pressure where excitons become stable states and electrons from the f-band, which have been thermally excited into the 5d conduction band, drop into the excitonic state and are no longer available for electric conduction. We have created an excitonic insulator, or excitonium, a term coined by Sir Nevil Mott [6]. With further pressure increase the resistivity drops again, until now the 4f electrons can enter the 5d band directly, which leads to a first order semiconductor-metal transformation.

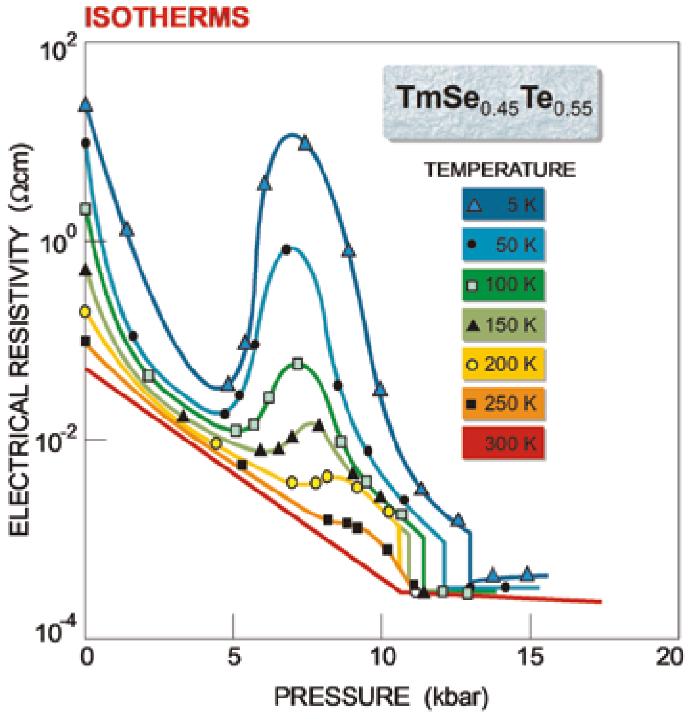


Figure 3. Isotherms of the electrical resistivity in $TmSe_{0.45}Te_{0.55}$ [4].

Exciton Condensation

Since for the exciton creation no energy is needed their number is enormous. But not all 4f electrons can form excitons, because as electric dipoles and according to the Pauli principle [8, 9] they repel each other. This goes so far that the formation of this incredible high concentration of excitons forces the whole crystal lattice to expand against the applied pressure. We show this in Fig. 4 where we measure the lattice constant (4a) (with strain gauges) and the expansion coefficient (4b) of the crystal in an isobar at 11.9 kbar. We observe that at about 230 K the lattice expands by 1.6 % isostructurally, an enormous amount. The expansion coefficient becomes negative, of course. We even think that the expansion is of first order (dashed – dot line), but the point by point measurement cannot reproduce this exactly, because we go from the semimetallic state to the excitonic state.

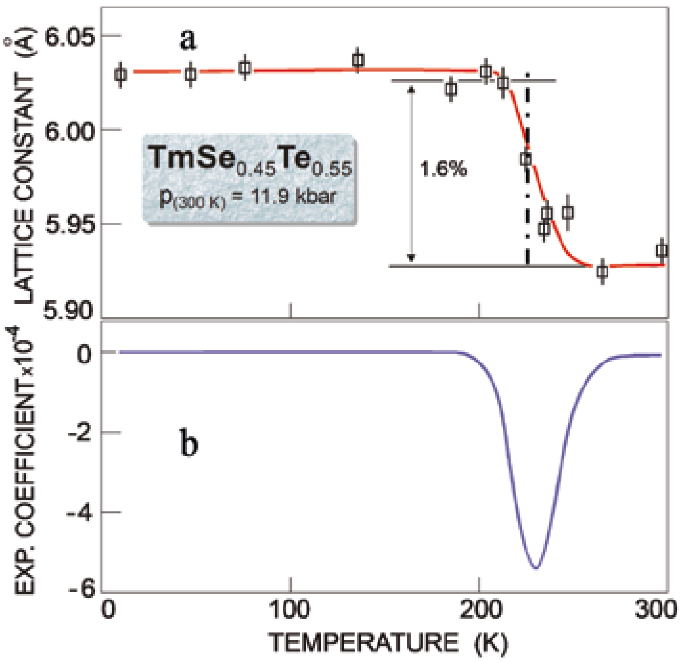


Figure 4. a,b. Isobar lattice constant and expansion coefficient.

We can estimate the maximal number of excitons with the help of Fig. 4 a and we observe that the lattice expansion occurs spontaneously when entering the excitonic phase. There must be an energy balance between the lattice energy causing the expansion and the electronic energy of the excitons. The energy balance can be described by the first equation in Fig. 5. We take the lattice constant change from Fig. 4 a to go from 5.93 Å to 6.03 Å, compute Δl/l and ΔV/V. We choose a pressure of 8.5 kbar and an E_B of 70 meV and compute the number of excitons $n_{ex} = 3.9\cdot10^{21}$ cm^{-3} (red field). We also can compute the number of Tm ions in the crystal in the fcc structure and it is $n_{Tm} = 1.8\cdot10^{22}$ cm^{-3} (yellow field). In other words the exciton concentration is about 22 % of the atomic density, an enormous amount of excitons. An exciton orbit can be computed from Bohr's radius for hydrogen and the dielectric constant $a_{ex} = 0.53\varepsilon = 18$ Å. It is quite clear that for such a large orbit we have an exciton overlap, an exciton band or an exciton condensation. Since the exciton couples to a phonon the condensation is a Bose condensation, not a Bose – Einstein condensation. We can also estimate the Bose condensation temperature shown in Fig. 5, where the general accepted formula yields $T_B = 130$ K the right order of magnitude. The holes of the exciton are in a narrow 4f-band and with a pressure change of 5 to 8 kbar (Fig. 3) one scans the width of the 4f-band [10]. The closing rate of the semiconductor gap has been measured to be dΔE/dp = -11 meV/kbar [3], so 3 kbar · 11 meV/kbar = 33 meV for the width of the narrow 4f-band. From this in turn we use the general estimate that a band width of 1.5 eV yields an effective mass of me and derive that a band width of about 30 meV corresponds to an effective hole mass $m_h \approx 50\ m_e$. The excitons are thus heavy bosons.

Here we want to make some remarks about this exciton condensation. Nobody in the world (to the best of our knowledge) has a comparable concentration of excitons, which exist as long as we can sustain the pressure and as the liquid Helium lasts, this means for days. We can make all kind of experiments in this condition, such as electrical conductivity, Hall effect, compressibility, heat conductivity, superfluidity, ultrasound velocity, phonon dispersion and specific heat [5]. Nobody else has these possibilities. But the experiments are very demanding, low temperature and simultaneous pressure and doing the experiment which one wants to make.

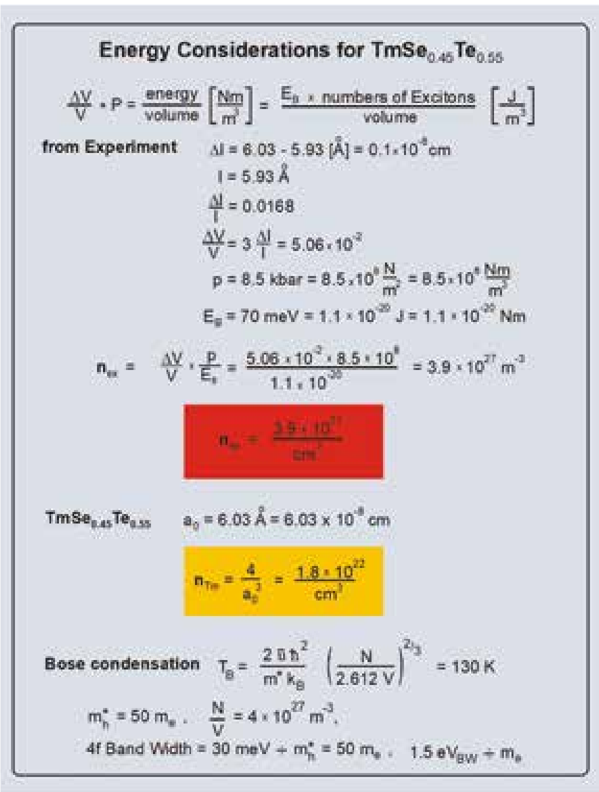


Figure 5. Calculation of the exciton concentration.

Phase diagram of semiconductor, excitonic insulator and semimetal

We plot in Fig. 6 the coexistence ranges of the intermediate valence semiconductor, the excitonic insulator and the intermediate valence semimetal. We see that the highest temperature for which the excitonic insulator exists is about 260 K and the pressure range is between 7 and 13 -14 kbar (pressures applied at room temperature). Experimentally one can only measure isobars in a clamped pressure cell. However, the isobars in Fig. 6 are no straight lines, because the pressure applied at room temperature relaxes somewhat at low temperatures. In the inset of Fig. 6 we see the Hall effect, which measures the free electron concentration in the 5d band. In the semimetallic state (curve M) at 13 kbar the electron concentration is about $3\cdot10^{21}$ cm^{-3}. For the excitonic insulator at 8 kbar the free electron concentration is about 10^{18} cm^{-3} because now the free electrons condense into the excitons and do not contribute anymore to the Hall effect. In fact we observe that the carrier concentration reduces by about 3 orders of magnitude, the same as has been observed in Fig. 3 for the electrical resistivity. The change in resistivity is thus mainly an effect in the carrier concentration though the mobility changes also somewhat [11]. The concentration of the excitons is then $3\cdot10^{21}$ cm^{-3} – 10^{18} cm^{-3} = $3\cdot10^{21}$ cm^{-3}, about the same as has been obtained in Fig. 3.

We can consider in an analogy a pot with soup. The pot is the hard surrounding of the crystal and inside is a soup of liquid excitons.

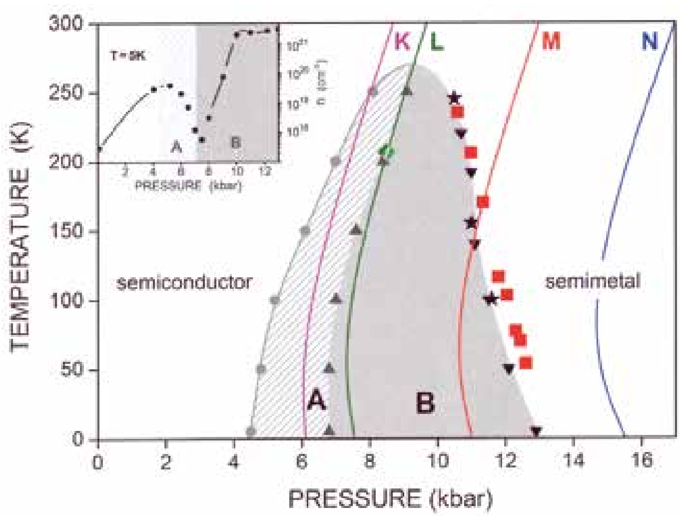


Figure 6. Temperature – pressure diagram of $TmSe_{0.45}Te_{0.55}$ with 3 regions: intermediate valence semiconductor, excitonic insulator (A, B), intermediate valence semimetal. The lines K, L, M, N represent isobars, which are curved since the pressure applied at 300 K relaxes somewhat at low temperatures. The inset shows the 5d free carrier concentration from a Hall effect in function of pressure and at 5 K [6, 11]. The red squares indicate the first order transitions into the semimetallic state.

Isotherm and compressibility

How can we get direct evidence for the condensed excitonic state? Typical for any liquid is its incompressibility. We can, for instance at 1.5 K, apply an increasing pressure to $TmSe_{0.45}Te_{0.55}$ and this is shown in Fig. 7 [10]. At first we cool at zero pressure from 300 K to 1.5 K and volume and lattice constant decrease. Then we increase pressure and measure the lattice constant with elastic neutrons through the pressure cell. Of course, lattice constant and volume decreases further, corresponding to a Birch-Mournaghan equation (red curve). This is a very time consuming experiment, because for each pressure change the pressure cell had to be heated to room temperature to change to a higher pressure and then cooled down again to adjust the sample in the neutron beam and wait for beam time. Therefore this experiment has only 4 points, but at the relevant pressures. As can be seen in Fig. 7 when entering the excitonic state the lattice constant remains unchanged with increasing pressure, which means a compressibility of zero. Taking experimental uncertainties into account, we have at least a compressibility just as for diamond. Thus we can take this experiment as evidence of an excitonic liquid.

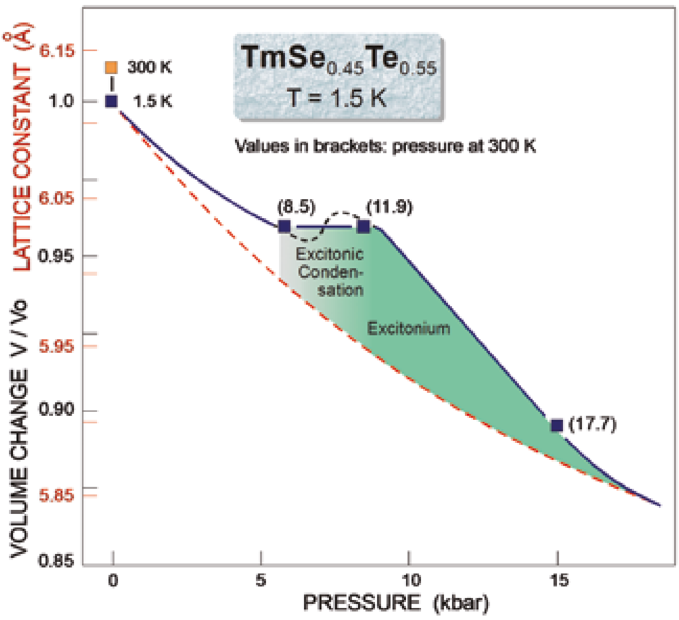


Figure 7. Isotherm at 1.5 K at relevant pressures. In brackets values at 300 K [10].

The specific heat

We are still describing the unexpected properties of the exciton liquid, inasmuch as nobody else in the world has such a large and permanent concentration of excitons: as $3.9 \cdot 10^{21}$ cm^{-3}. As we have stated already several times above, the excitons in this indirect semiconductor couple strongly to phonons in a triple particle entity of hole-electron and phonon as an exciton-polaron. But when the phonons couple to the heavy excitons with effective masses of the holes around $m_h \approx 50\ m_e$ they become more or less localized like a local mode and do no longer contribute significantly to the specific heat. The phonon spectrum must get renormalized. An essential part of the Debye spectrum of the specific heat is missing.

So in Fig. 8 (blue curve) we show the measured specific heat under pressure corresponding to curve N in Fig. 6, in the semimetallic region. It represents practically a Debye curve and stays outside the excitonic region. In contrast, the red curve in Fig. 8 corresponds to curve K in Fig. 6, which enters the excitonic region at 250 K. And it is exactly at this temperature and below (indicated with an arrow) where the red curve strongly deviates form a Debye curve. Nobody has ever seen such a specific heat curve. The red curve in Fig. 8 is in fact a computer simulation of the specific heat of the experimental curve K in Fig. 6 under the assumption of a linear decrease of the optical phonon density of states, as shown in the inset of Fig. 8 [6]. So the optical phonons contribute really less and less with decreasing temperature to the specific heat. The acoustic phonons more or less stay the same, but with a small change in the Debye temperature Θ.

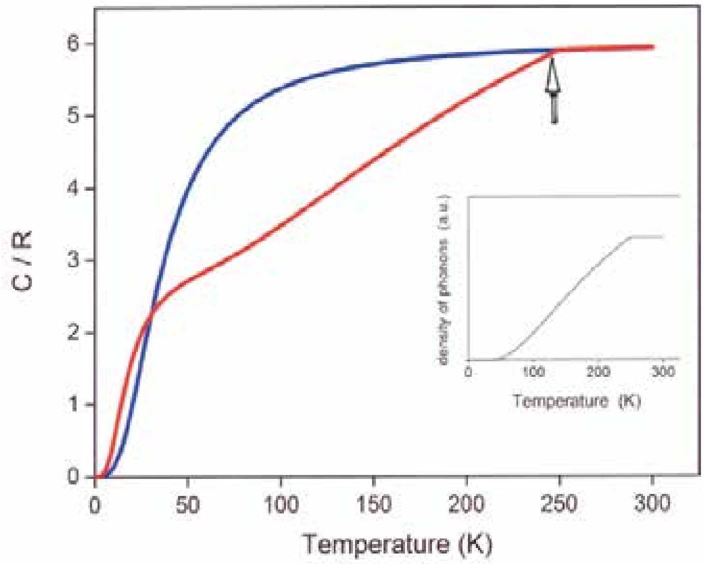


Figure 8. The specific heat along curve N (semimetallic) in Fig. 6 (blue) and along curve K (excitonic). in Fig. 6 (red). The inset shows an assumed linear temperature dependence of the optical phonon density of states [6].

Heat conductivity and superfluidity in the excitonic liquid.

Above we have described the properties of the condensed exciton-polaron liquid, the unique way of creating such a large number of excitons that they interact with each other. With this huge concentration, $n_{ex} = 3.9 \cdot 10^{21}$ cm^{-3} the excitons as electric dipoles repel each other to such an extent that they refuse to come any closer and thus exhibit the phenomenon of a zero compressibility for increasing pressure. In addition, since every exciton couples to an optical phonon and the excitons have such a large hole mass as $m_h \approx 50\ m_e$ that the optical phonons no longer are running waves but become quasi a local mode. In this case their dispersion is no longer $\omega = ck$ and the Debye theory of specific heat will be very unusual. Nevertheless the material is still transporting heat, e.g. with acoustic phonons or exciton-polarons.

To measure the heat conductivity under pressure is not a simple task and we believe that we made such a measurement for the first time. The experimental setup is described in detail in Ref. [12]. But the motivation to measure the heat conductivity and also the thermal diffusivity (not discussed in this paper) are some long standing theories, which never have been proven experimentally. They are from Ref. [9] and Kozlov and Maksimov, [13]. To state the essence of the theory: an excitonic liquid has the possibility to become a superfluid. The argument in simple terms is the following.

There is a similarity between pairs of particles: two electrons can condense and produce superconductivity, an electron hole pair (exciton) can upon condensation result in superfluidity, just as in ^{4}He [14]. A positron pair should also result in superconductivity, but no such experiment is known. The experimental test for superfluidity is a divergence of the heat conductivity, which, for zero temperature becomes infinite. The onset of superfluidity will be, however at some reasonable temperature.

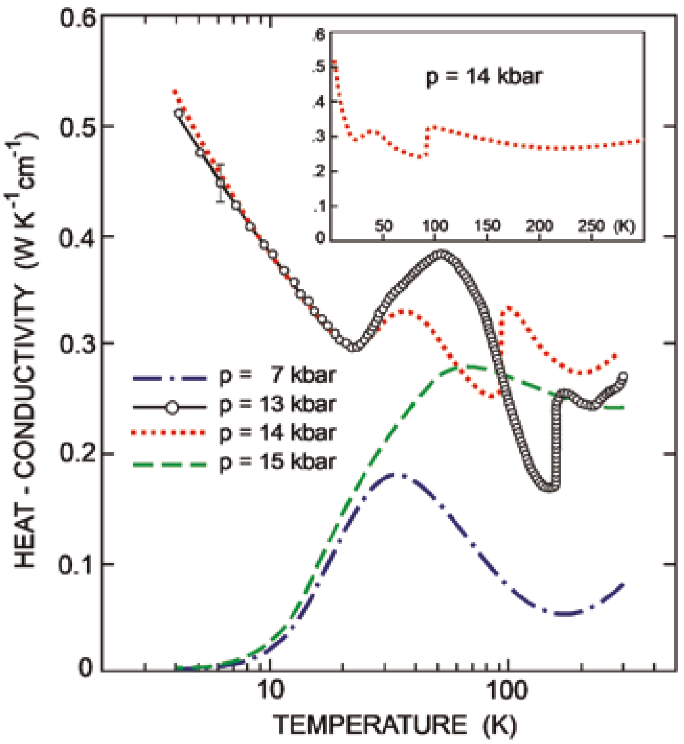


Figure 9. Heat conductivity λ of $TmSe_{0.45}Te_{0.55}$ for various pressures in function of temperature. Dotted and full line in the excitonic region, dashed in the semimetallic region and dash – dotted line in the semiconducting phase. The inset shows the heat conductivity at 14 kbar in a linear scale [12]

The essence to measure heat conductivity are isobars between 4 K and 300 K at various pressures. We show the results of measurements of the heat conductivity λ with isobars at 4 different pressures, one in the semiconducting range (compare Fig. 6) with 7 kbar, one in the semimetallic range at 15 kbar, both outside the excitonic region, and at two pressures 13 and 14 kbar within the excitonic range. Temperature has been measured automatically for each degree. The heat conductivity depends on the specific heat c_v and l_{ph} in direction x, the mean free path for phonon scattering. In short, for normal materials, l_{ph} will increase with decreasing temperature because the density of phonons decreases and we have Umklapp processes involving 3 phonons. But the specific heat c_v definitely will go towards zero for zero temperatures, just as the third law of thermodynamic demands. Thus the heat conductivity outside the excitonic region will display a maximum near 50 K, as well for the semiconducting range (7 kbar) as for the metallic range (15 kbar) and this is displayed in Fig. 9 and this behavior is quite normal. The difference of the heat conductivity near 300 K for both cases is due to the electronic part of the heat conductivity in the metallic state and it corresponds roughly to the Wiedemann – Franz relation. This gives confidence to the measurements. We continue with the heat conductivity in the excitonic region at 13 and 14 kbar. We observe an unexpected downward jump in a first order transition when entering the excitonic phase. Consulting Fig. 6 it is obvious that at different pressures one enters the excitonic phase at different temperatures. At these temperatures and pressures one enters the insulating excitonic phase mainly from the semimetallic phase, thus with a metal – insulator transition (red squares in Fig. 6). The downward jumps in the heat conductivity λ reflect the loss of the electronic part of the heat conductivity. The fascinating aspect of the heat conductivity in the excitonic region is the sharp increase of λ below about 20 K, quite in contrast with the λ outside the excitonic region. Since λ follows mainly the specific heat c_v and the phonon mean free path l_{ph}, and c_v nevertheless must go to zero for T→0, it is the phonon mean free path which goes faster to infinite than c_v towards zero. Finally it means that the phonon mean free path becomes infinite. When one makes a heat pulse at one end of the crystal the excited phonon transports its energy without scattering on other phonons to the other side of the crystal, meaning an infinite heat conductivity. Instead of phonon scattering in a diffuse manner the heat conductivity occurs ballistically via a highly directional quantum mechanical wave, the second sound. This is, however, only possible if the concentration of phonons as running waves is substantially reduced, because most of them couple to the heavy excitons as exciton-polarons, as we have seen before and thus more or less correspond to local modes. The fact that the heat conductivity in the excitonic region does not go towards zero for zero temperature means that the heat conductivity in this range does not follow classical physics, but quantum mechanics.

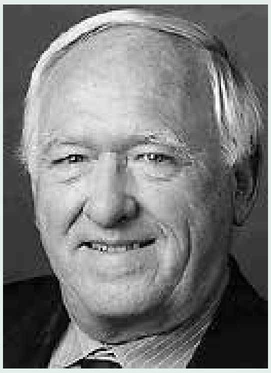
Unfortunately the measurements were limited to 4.2 K, because at the time of the measurements one did not realize the implications. In any case 20 K, the onset of the sharp increase of λ with decreasing temperature can be considered as the onset of superfluidity, which, however, is different from the one of ^{4}He, inasmuch as there the onset of superfluidity is a first order transition [14]. For our exciton case we propose a superthermal current in the two – fluid model, where the superfluid part increases gradually towards zero temperature [14]. A λ-anomaly in the specific heat as in the first order Bose-Einstein transition in ^{4}He is here not to be expected and also not found [14].

The proposed evidence of superfluidity within the condensed excitonic state necessitates an additional excitation spectrum of other quasiparticles, namely rotons or vortices [14]. λ_{tot} is the sum of individual contributions and below about 20 K $\lambda_{tot} = \lambda_{ph} + \lambda_{ex}$. λ_{ph} is the heat conductivity due to uncoupled phonons, which is proportional to T^3 and can be neglected compared to λ_{ex} at low temperatures. Thus we obtain for λ_{ex} an Arrhenius law for the increase of the heat conductivity towards zero temperature $\lambda_{ex} \propto \exp \Delta/k_BT$. The activation energy or the gap Δ is 1 meV or about 10 K. The application of heat in the heat conductivity experiment can excite quasiparticles, e.g. rotons with gap energy of about 10 K, which is the right order of magnitude. In superfluid ^{4}He the roton gap is 8.65 K [15].

Conclusion

By choosing a special rare earth compound, $TmSe_{0.45}Te_{0.55}$, which has naturally a small energy gap $\Delta E \approx 120$ meV between $4f^{13}$ and 5d band, so that the tails of the wave functions overlap somewhat, an intermediate valence semiconductor could be created. The originally localized 4f state thus becomes a narrow band with width 33 meV and an excitonic level with binding energy $E_B \approx 60$ meV can be thermally populated. The hole state in the 4f band has a mass of about $m_h \approx 50\ m_e$, thus the exciton is a heavy boson. By applying external pressure, the bottom of the 5d conduction band with its exciton level can be lowered exactly so much that the exciton level at X in the Brillouin zone has the same energy as the uppermost 4f electron at Γ. Under this condition electrons from the 4f band can spill without the need of further energy into the excitonic state and cause an enormous amount of excitons, $3.9 \cdot 10^{21}/cm^3$ without any further excitation. As mentioned already these excitons have a heavy hole mass and are not very mobile. For momentum conservation each exciton must couple to a phonon and is thus an exciton-polaron. As a consequence, these phonons become nearly local modes and the phonon dispersion must be renormalized. In fact the specific heat under pressure in the excitonic region looks completely different than a normal Debye distribution.

Since 1965 theories exist that an exciton liquid can become a superfluid, but these theories have never been verified experimentally, mainly because laser excited excitons in other experiments have orders of magnitude smaller exciton concentrations than we have. So it needed this large and constant exciton-polaron concentration to be able to look for superfluidity. The best test for superfluidity is a measured divergence of the heat conductivity, which we found to occur below 20 K and for 13 and 14 kbar. To remind you, the highest T_c for superfluidity was so far limited to 2.17 K in ^{4}He. We now find a factor 10 higher. And it is remarkable that in the same experiment, just by varying the pressure, a classical heat conductivity outside the excitonic region, and a quantum mechanical heat conductivity in the excitonic region can be created in which the exciton-polaron liquid takes over the heat conductivity below 20 K and becomes superfluid.



From 1973, **Peter Wachter** was full professor of physics at the Laboratory for Solid State Physics at ETH Zurich. He retired in 1999.

Born on 16 March 1932 in Munich (D), he studied physics at the Technical University of Munich, where he graduated in 1956 and completed his PhD in 1960. He then spent two years as an assistant professor at the Radiation and Solid State Laboratory of New York University in New York, USA. From 1963 he worked at the Laboratory for Solid State Physics at ETH Zürich in the field of ferromagnetic semiconductors. In 1964 he discovered the so-called "Busch-Wachter effect", internationally known as the "red shift of ferromagnetic semiconductors". In 1969 he habilitated and received several offers as a professor at German universities. In 1972 he became an associate professor at ETH Zurich. He worked in the field of experimental Solid State Physics. During the years 1976-1996 he was visiting professor at the Université des Séances et Techniques du Langedoc, Montpellier (F) (1976), the Academy of Sciences of the USSR (1980), the Academia Sinica (People's Republic of China) (1983) and the Tohoku University in Sendai (J) (1996).

He is author of more than 550 publications and has given more than 272 invited lectures. He has co-edited *Solid State Communications*, *Physica B* and *Lanthanides and Actinides*. Two handbook articles on "*Europium Chalcogenides: EuO, EuS, EuSe and EuTe*" (1979) and "*Intermediate Valence and Heavy Fermions*" (1994) have been published.

1997-2007 he was nominated as "European Physicist", 1998 he became Honorary Professor of the Henan University, China, 16 national and international Professorships of scholars.

Theories

There are various theories concerning excitons and exciton condensation, especially when phonons are involved [16-21]. The limited space does not permit to comment them.

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Geschichte und Philosophie der Physik (25)

Kosmos in der Kammer – Ausstellung zur Kosmographie des 16. Jahrhunderts in der Zentralbibliothek Zürich

René Schurte, Zentralbibliothek Zürich

Die Zentralbibliothek Zürich hat den Kosmos in die Kammer geholt, und dies in materieller wie in virtueller Form. Die Ausstellung in der Schatzkammer der Zentralbibliothek, die noch bis zum 7. Dezember 2019 besichtigt werden kann, zeigt Schätze der Kosmographie des 16. Jahrhunderts aus den Sammlungen der Zentralbibliothek und von weiteren Leihgebern.

Das 16. Jahrhundert war eine Zeit grosser wissenschaftlicher Veränderungen. Berichte über neu entdeckte geographische Räume, aber auch neue Erkenntnisse und Entdeckungen in den Naturwissenschaften, namentlich in der Astronomie, stellten althergebrachte Vorstellungen und das bisherige Weltbild in Frage. Ebenso wurden die Messungen und Methoden immer besser, infolgedessen entstanden im 16. Jahrhunderts die ersten modernen Weltkarten und Atlanten.

Kosmos in der Kammer

Die Ausstellungsmacher haben versucht, den Eindruck einer kosmographischen Schatzkammer zu vermitteln. In der frühen Neuzeit wurden an Fürstenhöfen, aber auch in Städten Kunstkammern eingerichtet, in denen Kuriositäten, Präparate, Bücher, Karten und wissenschaftliche Instrumente gesammelt wurden. In Zürich befand sich eine solche Kammer in der Wasserkirche, dem früheren Standort der Stadtbibliothek. Zu jeder dieser Kammern gehörten auch Globen, die den Kosmos, die Welt als Ganzes, in der Kammer repräsentierten.

Johann Meyer: Abriss der Kunst-Kammer auf der Wasser Kirchen in Zürich. Entwurf für das Neujahrsblatt der Stadtbibliothek Zürich 1687, Zentralbibliothek Zürich, ZEI Njbl. 22

So zeigt auch die Ausstellung neben Büchern und Karten weitere kosmographische Objekte. Als erstes dürfte eine monumentale astronomische Uhr aus dem Zürich des 17. Jahrhunderts ins Auge fallen, die neben einem Zifferblatt zwei Anzeigen der Planetenstände enthält. Gleich daneben ist das kleinste Objekt der Ausstellung leicht zu übersehen. Es handelt sich um einen Siegelring mit dem Wappen des Zürcher Antistes Heinrich Bullinger (1504–1575). Die Inschrift auf dem Ring lautet «Vom Aufgang der Sonne bis zu ihrem Niedergang sei gelobet der Name des Herrn». Wenn man den Ring aufklappt, macht man eine überraschende Entdeckung: Darin befindet sich eine winzige Sonnenuhr, geschmückt mit einem Christusbild. Diese drei Elemente – Inschrift, Christusbild und Sonnenuhr – zusammen ergeben eine Kombination von christlichem und kosmographischem Blick auf die Welt.

Versteckte Sonnenuhr im Fingerring des Reformators Heinrich Bullinger, Zürich 1525, Zentralbibliothek Zürich, DEP 403.a

Das Prunkstück der Ausstellung, das auch als Titelbild die Begleitbroschüre ziert, ist nur virtuell vorhanden: Der St. Galler Globus, der zwar Eigentum der Zentralbibliothek ist, sich aber als Dauerdepositum im Zürcher Landesmuseum befindet, konnte aus konservatorischen Gründen und aufgrund seiner schieren Grösse (Höhe 2.33 Meter) nicht in die Zentralbibliothek transportiert werden. Dafür ist er in der Ausstellung gleich doppelt virtuell präsent: Sowohl vom Original wie von der originalgetreuen Replik, die in der St. Galler Stiftsbibliothek bewundert werden kann, wurden digitalisiert und können per Touchscreen bewegt und von allen Seiten und mit allen überraschenden Details bewundert werden.

Was bedeutet Kosmographie?

Der bekannteste geographische Text der Antike, die «Geographia» («Erdbeschreibung») des Claudius Ptolemäus (2. Jh. n. Chr.), wurde im 15. Jahrhundert im Westen neu entdeckt. Sein erster Übersetzer, Jacopo d'Angelo, wählte 1406 für dieses Werk allerdings den Titel «Cosmographia». Damit brachte er zum Ausdruck, dass die Methode des Ptolemäus sich nicht auf eine reine Erdbeschreibung beschränkt, sondern die Erde mit Hilfe kosmischer, also astronomischer Phänomene vermisst. Kosmographie meint somit die Vorgehensweise, die Gestalt der Erde in Abhängigkeit von Himmelsbeobachtungen zu beschreiben. Tatsächlich gehen wir bis heute kosmographisch vor: Die Festlegung der Längen- und Breitengrade bedient sich der Vermessung der Position der Gestirne, allen voran der Sonne.

Die Kosmographie des 16. Jahrhunderts verfolgte das Ziel, den Kosmos, also Erde und Himmel, als Ganzes zu verstehen und zu erforschen. In der Ausstellung wird dieses Vor-gehen repräsentiert durch zwei Globen von Gerhard Mercator (1512–1594). Mercator war ein innovativer Kosmograph und Kartograph, der unter anderem möglichst praktische Hilfsmittel für die Navigation bereitstellen wollte. Deshalb legte er den Nullmeridian dort fest, wo magnetischer und geographischer Nordpol in einer Linie stehen, und entwickelte eine Kartenprojektion, in der sich Längen- und Breitengrade immer im 90 Grad-Winkel schneiden.

Mercator war auch Globenbauer, und in der Ausstellung können ein Himmels- und ein Erdglobus von 1541 bzw. 1551 aus seiner Produktion bewundert werden. Der Erdglobus ist in Wahrheit ein kombinierter Erd- und Himmelsglobus, auf dem die Darstellung der Kontinente und himmlischer Phänomene (Ekliptik, Sternbilder) vereint ist, und somit ein kosmographischer Globus.

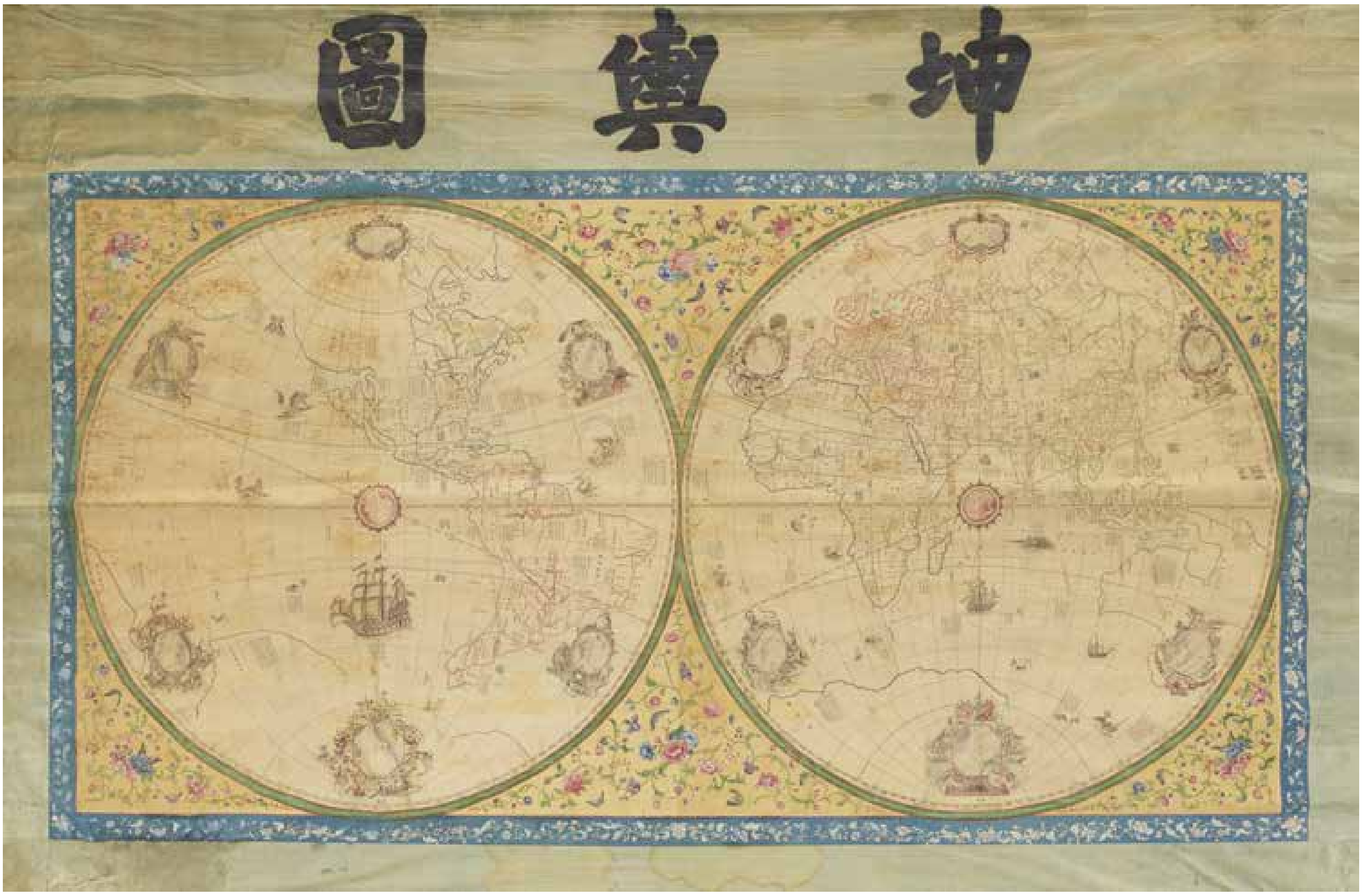
Nebst all diesem war Mercator auch der Urheber der Karte, die die Vorlage des St. Galler Globus bildete. Da man den St. Galler Globus dank der digitalen Version von Nahem studieren kann, stellt man fest, dass auch auf diesem Globus Himmelsphänomene aufgeführt sind. Dieser Globus war somit ebenfalls ein kosmographisches Objekt. Er diente nicht nur der Darstellung der Erde, sondern konnte dank seiner Mechanik auch als kosmographisches Messinstrument eingesetzt werden.

Kosmographie in der Schweiz und in Zürich

In der Ausstellung «Kosmos in der Kammer» sind die «Stars» des 16. Jahrhundert präsent: Neben Mercator sind u. a. weltbekannte Namen wie Tycho Brahe, Sebastian Münster oder Abraham Ortelius mit Werken vertreten, die Meilensteine der Wissenschaftsgeschichte sind. Auch eine Ausgabe von «De revolutionibus orbium coelestium» von Nikolaus Kopernikus, einem buchstäblich «revolutionären» Werk, darf natürlich nicht fehlen.

Daneben präsentiert die Ausstellung aber auch weniger bekannte Namen und weniger geläufige Seiten von bekannten Personen. Besonderes Augenmerk wird dabei auf Schweizer Persönlichkeiten gerichtet. Vertreten ist etwa der St. Galler Reformator und Humanisten Joachim Vadian (1484–1551), der auch astronomische Vorlesungen hielt und dessen geographisches Werk «Epitome trium terrae partium» 1534 von Froschauer in Zürich gedruckt wurde. Auch der erste Atlas der Schweiz, die «Landtaflen» von Johannes Stumpf (1500–1577/78), 1574 bei Froschauer gedruckt, kann bewundert werden.

Überraschen dürfte viele ein Eintrag des Winterthurer Pfarrers und Astronomen Bernhard Lindauer (1520–1581) in seiner handschriftlichen Chronik, die in der Zentralbibliothek aufbewahrt wird. Lindauer berichtet, dass am 7. November 1572 «ein nüwer grosser heiterer stern» im Sternbild Cassiopia beobachtet wurde. Es handelt sich um jenes Phänomen, das von Tycho Brahe ebenfalls – wenn auch einige Tage später als Lindauer – beobachtet und als «Nova» («neuer Stern») gedeutet wurde. Dadurch wurde die herkömmliche Überzeugung, der Fixsternhimmel sei unveränderlich, in Frage gestellt. Heute wird das Phänomen als Supernova bezeichnet.



Kun yu tu («Karte der Erde») China 1750/1800, Zentralbibliothek Zürich, Wak 342

Perspektivenwechsel

Zum Abschluss der Ausstellung weist der Blick über das 16. Jahrhundert hinaus: Die Zentralbibliothek hat Anfang dieses Jahres eine monumentale chinesische Weltkarte als Geschenk erhalten und die Gelegenheit ergriffen, dieses imposante Objekt erstmals der Öffentlichkeit zu präsentieren. Die sorgfältig gestaltete Karte wird auf das 18. Jahrhundert datiert, geht aber auf eine ältere europäische Karte als Vorlage zurück.

Die letzte Station des Rundgangs bietet einen Perspektivenwechsel. Unser heutiges Weltbild ist stark von den Erkenntnissen und Fortschritten des 16. Jahrhunderts geprägt. Besonders die Projektion Mercators ist auf unseren Weltkarten allgegenwärtig. Aber natürlich gibt es viele andere Möglichkeiten, die Welt zu sehen und darzustellen. Dies wird mit einigen Beispielen aus anderen Kulturkreisen und alternativen Weltdarstellungen der Gegenwart verdeutlicht. Besucherinnen und Besucher verlassen die Kammer hoffentlich mit vielen spannenden Eindrücken und einem neuen Blick auf den Kosmos.

Mehr als eine Bibliothek:
Die Zentralbibliothek Zürich

Was hat die ZB mit Schach zu tun? Mit Sports Illustrated? Fantastischen Wesen aus dem Kloster Rheinau? Oder mit dem Thema Seide? Die Vielfalt der ZB kennt keine Grenzen.

Als die grösste Stadt-, Kantons- und Universitätsbibliothek der Schweiz steht die ZB allen offen. Über sechs Millionen gedruckte Dokumente aller Art stehen zum Studium bereit. Fast 90’000 elektronische Zeitschriften und Bücher sind hier zugänglich. Dazu gehören 830 Arbeitsplätze, kompetente Beratung, Führungen und Schulungen sowie ein breit gefächertes Aus- und Weiterbildungsprogramm für Bibliothekarinnen und Bibliothekare.

Doch die ZB ist mehr als eine Bibliothek. Als beliebter Raum des Lernens steht sie zahlreichen Studierenden, aber auch der breiten Bevölkerung für Begegnungen, für den Informationsaustausch und für kulturelle Veranstaltungen zur Verfügung. Als Museum führt sie seit Jahrzehnten zudem kleine, aber feine Ausstellungen durch und ist damit auch ein wichtiger Kulturort auf dem Platz Zürich. Entdecken Sie die spannenden Schätze der Zentralbibliothek Zürich!

Neben der bereits erwähnten Nürnberger Ausgabe von Kopernikus ‚De revolutionibus orbium coelestium‘ findet der an der Geschichte der Physik Interessierte weitere Preziosen wie zum Beispiel eine Buchausgabe aus dem Jahre 1684 mit dem Konterfei des Schweizer Universalgenies Jost Bürgi. Die wissenschaftlichen, technischen und neuerdings auch erkannten soziologischen Leistungen Bürgis als Vorläufer des dualen Bildungsmodells, die bislang von der Geschichtsschreibung unter Wert behandelt wurden, sollen alljährlich an seinem Geburtsort Lichtensteig im Toggenburg mit einem Symposium aufgezeigt werden. Die SPG beteiligt sich gerne an den Veranstaltungen, da Johannes Kepler sehr eng mit Bürgi zusammenarbeitete.

B. Braunecker

Abbildung: Frontispiz mit dem Porträt von Jost Bürgi, aus: Benjamin Bramer: Apollonius Cattus, Oder: Kern der gantzen Geometrieæ Kassel 1684. Zentralbibliothek Zürich, Signatur NE 1827: 1

Participer au Teacher Programme du CERN – L'expérience d'un prof suisse

Philippe Kobel – maître de Physique au gymnase du Bugnon, Lausanne, philippe.kobel@gmail.com

Cela faisait quelques années que j'avais entendu parler du programme international du CERN pour enseignants comme l'une des formations continues à faire absolument. Enfin, 70 ans après l'idée fondatrice du CERN (merci Louis De Broglie pour sa vision en 1949), j'ai eu la chance d'être sélectionné pour vivre deux semaines au CERN en participant à l'« International Teacher Weeks (ITW) » qui a eu lieu du 4 au 17 août dernier. On pourrait d'ailleurs le rebaptiser « SUPER ITW » (les physiciens des hautes énergies adorent ce préfixe), car à l'image du CERN, qui est le centre de recherche le plus international au monde, 47 enseignants de 38 pays différents avaient également été invités.

Suivirent deux semaines extrêmement intenses en apprentissage et en rencontres. Le programme, minuté à perfection et structuré avec soin par les organisateurs Jeff Wiener et Anja Kranjc Horvat, a couvert tous les aspects du CERN: Physique des particules, boson de Higgs, accélérateurs, détecteurs, analyse de données et computing, applications médicales. Nous avons eu droit à des conférences par des experts du CERN dans tous ces domaines, le tout équilibré par des visites et des ateliers éducatifs. De quoi répondre à toutes les questions de nos élèves et leur concocter des activités pratiques, comme la construction d'une chambre à brouillard, l'analyse de données d'une simulation de détecteur ou de la programmation avec des données réelles ! J'ai ainsi pu (enfin !) construire ma première chambre à brouillard, rendant visible les traces de particules invisibles. De plus, le LHC étant actuellement en phase de travaux (visant à augmenter le nombre de protons par paquets), nous avons pu visiter les détecteurs CMS, ALICE ainsi que le décélerateur d'anti-protons !

Mais l'ITW est aussi une expérience humaine. Etre baigné dans cet environnement international de profs « ultra-motivés » est une source d'inspiration constante. Le moto du CERN, « science pour la paix » est devenu concret pour nous, car la curiosité humaine et l'émerveillement nous a tous réuni par-delà les frontières. Bien sûr, les soirées internationales y ont aussi bien contribué et en tant que « local boy », j'ai eu le privilège de pouvoir guider mes collègues dans quelques repères bien genevois.

Après ces deux semaines, j'ai le sentiment que le CERN est devenu un peu chez moi. Je ne me perds (presque) plus dans ces couloirs et je ne pense plus qu'à une chose : y revenir avec mes élèves pour une visite et un atelier S'Cool Lab !

Visite du détecteur CMS (Compact Muon Solenoid).

Les programmes pour enseignants du CERN

« Les enseignants sont les personnes les plus importantes pour nous au CERN. », souligne Dr. Jeff Wiener, le manager des programmes pour enseignants. Car la plupart des physiciens au CERN sont là parce qu'ils ont eu un enseignant qui leur a fait découvrir et aimer la physique. C'est eux qui pourront responsabiliser les élèves face aux enjeux globaux de demain et leur faire réaliser l'importance de la recherche fondamentale.

Le CERN propose deux types de programmes (formations continues) pour enseignants : les programmes « nationaux » d'une semaine environ pendant l'année scolaire et les programmes « internationaux » de deux semaines pendant l'été. Ces derniers sont dispensés en juillet (sous le nom d' « International teacher programme ») et en août (« International teacher weeks »). A noter : bien que le nom des deux programmes internationaux diffère, il s'agit exactement de la même formation, de quoi vous laisser le choix selon vos disponibilités. Les programmes internationaux sont uniquement en anglais et n'engagent aucun frais de participation (les frais d'hébergement et repas étant couverts par le CERN).

Pour vous inscrire aux programmes internationaux : Soumettre votre application jusqu'au 12 janvier 2020
http://teachers.cern/itp/international-teacher-programmes
Pour vous inscrire aux programmes nationaux :
http://teachers.cern/ntp/national-teacher-programmes
Un programme national suisse sera organisé en 2020 !

A propos de Philippe Kobel

Après un doctorat en astrophysique sur la magnétisme solaire, Philippe Kobel a poursuivi de recherches sur le phénomène de cavitation à l'EPFL et participé à plusieurs campagnes de vols paraboliques de l'ESA. En parallèle, il a lancé le projet éducatif itinérant GalileoMobile, rendant visite à des écoles d'Amérique du Sud, d'Inde et d'Afrique pour réaliser des activités pratiques sur l'astronomie, inspirer les enfants à observer les étoiles et se sentir unis sous un même ciel. C'est là que sa conviction pour l'enseignement et le partage de ses expériences s'est renforcée. Depuis 2014, il enseigne avec passion la physique au gymnase du Bugnon à Lausanne. bubbles.epfl.ch , galileo-mobile.org, youtube (PhilZiK)

Der VSMP stellt sich vor

Christian Stulz, Präsident DPK

VSMP
SSPMP
SSIMF
Verein Schweizerischer Mathematik- und Physiklehrkräfte
Société Suisse des Professeurs de Mathématique et de Physique
Società Svizzera degli Insegnanti di Matematica e di Fisica

Der *Verein Schweizerischer Mathematik- und Physiklehrkräfte* VSMP und die *Schweizerische Physikalische Gesellschaft* SPG haben 2016 eine Verstärkung der Zusammenarbeit vereinbart und ermöglichen seither eine attraktive Doppelmitgliedschaft. Um sich ein Bild der jeweils anderen Organisation machen zu können, stellen sich diese gegenseitig in ihren Vereinszeitschriften (*VSMP Bulletin* und *SPG Mitteilungen*) vor. Ziel ist es, die Physikerinnen und Physiker sowie Physikinteressierte der Schweiz besser einzubinden und zu vernetzen. Dabei entstehende Synergien können genutzt werden, um noch besser auf aktuelle Fragen und Probleme der Physik einzugehen. Insbesondere soll die Zusammenarbeit auch dazu beitragen, die Attraktivität der Physik für den akademischen Nachwuchs (Gymnasialschülerinnen und Gymnasialschüler) zu steigern.

Der VSMP und seine Kommissionen

Der VSMP ist als Fachverband dem VSG (Verein Schweizerischer Gymnasiallehrerinnen und Gymnasiallehrer) angegliedert und ist in der ganzen Schweiz tätig. Die fünf ständigen Kommissionen des VSMP sind im betreffenden Fach (Physik, Mathematik) und der entsprechenden Sprachregion tätig. Sie nehmen herausgebende Tätigkeiten war, organisieren Weiterbildungen und arbeiten bei Fragen auf politischer oder administrativer Ebene der Bildung der Sekundarstufe 2 in ihren Fachgebieten mit. Diese fünf Kommissionen sind:
- Deutschschweizerische Mathematikkommission DMK
- Commission Romande de Mathématique CRM
- Commissione di Matematica della Svizzera Italiana CMSI
- Deutschschweizerische Physikkommission DPK
- Commission Romande de Physique CRP

Die Mitglieder des VSMP und der Kommissionen setzen sich aus Lehrpersonen aus Gymnasien und Dozierenden aus Hochschulen und Fachhochschulen aus den Gebieten Mathematik und Physik zusammen.

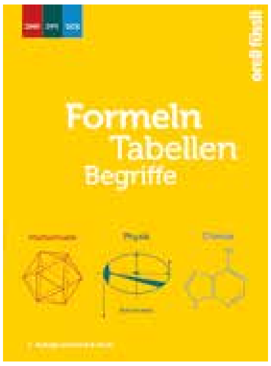
Die Ziele des VSMP

Die Ziele des VSMP sind die Förderung der wissenschaftlichen Kultur und Denkweise sowie des Unterrichts in Mathematik und Physik. Weiter spielt auch die Förderung des Austausches von Ideen, Erfahrungen und Informationen unter den Mitgliedern eine wichtige Rolle. Der Verein engagiert sich auch bei Weiterbildungen für seine Mitglieder und weiteren Lehrpersonen, um ein hohes Ausbildungsniveau in seinen Disziplinen gewährleisten zu können. Der VSMP bietet sich als politische Standesvertretung an und wahrt die Berufsinteressen der Mittelschullehrpersonen insbesondere auch in Zusammenarbeit mit dem VSG.

Das Bulletin

Das periodisch erscheinende Bulletin sichert den Kontakt zwischen den Mitgliedern des VSMP und weiteren Interessierten. Seit 1990 erlaubt es die Publikation von wissenschaftlichen Artikeln, persönlichen Stellungnahmen, Leitartikeln und administrativen Mitteilungen. Das Bulletin steht auf der Webseite des VSMP als PDF zum Download zur Verfügung.

Die Publikationen



Die Herausgabe von Unterrichtswerken ist eine der wesentlichen Aktivitäten der Kommissionen des VSMP. Diese Veröffentlichungen sind ein konkreter Beitrag zur Koordination des Unterrichts, wobei die Autoren und Autorinnen stets dem notwendigen Nebeneinander unterschiedlicher pädagogischer Lehrmeinungen Rechnung tragen. In Physik publiziert der Verein die Formelbücher «Formeln, Tabellen, Begriffe» und «Fundamentum Mathematik und Physik», die beide als E-Book und auch in einer englischen Übersetzung erhältlich sind. Das Aufgabenbuch «Physik anwenden und verstehen» ist eine reichhaltige Aufgabensammlung für das Grundlagenfach Physik am Gymnasium. Das Werk ist auf die Bedürfnisse der Schweiz ausgerichtet und deckt mit insgesamt 1000 Aufgaben alle Lehrplanthemen ab. In den französischen und italienischen Sprachregionen sind die Formelbücher «Formulaires et tables» und Formulari e tavole», neben verschiedenen anderen Monografien, zu erwähnen. Weiter gehören Lehr- und Aufgabenbücher aus der Mathematik zu den Themen Algebra, Stochastik (inkl. Kombinatorik), Geometrie (inkl. Vektoren) und Analysis (Differential- & Integralrechnung, Differentialgleichungen) zu den Publikationen des VSMP.

Die weiteren Aktivitäten

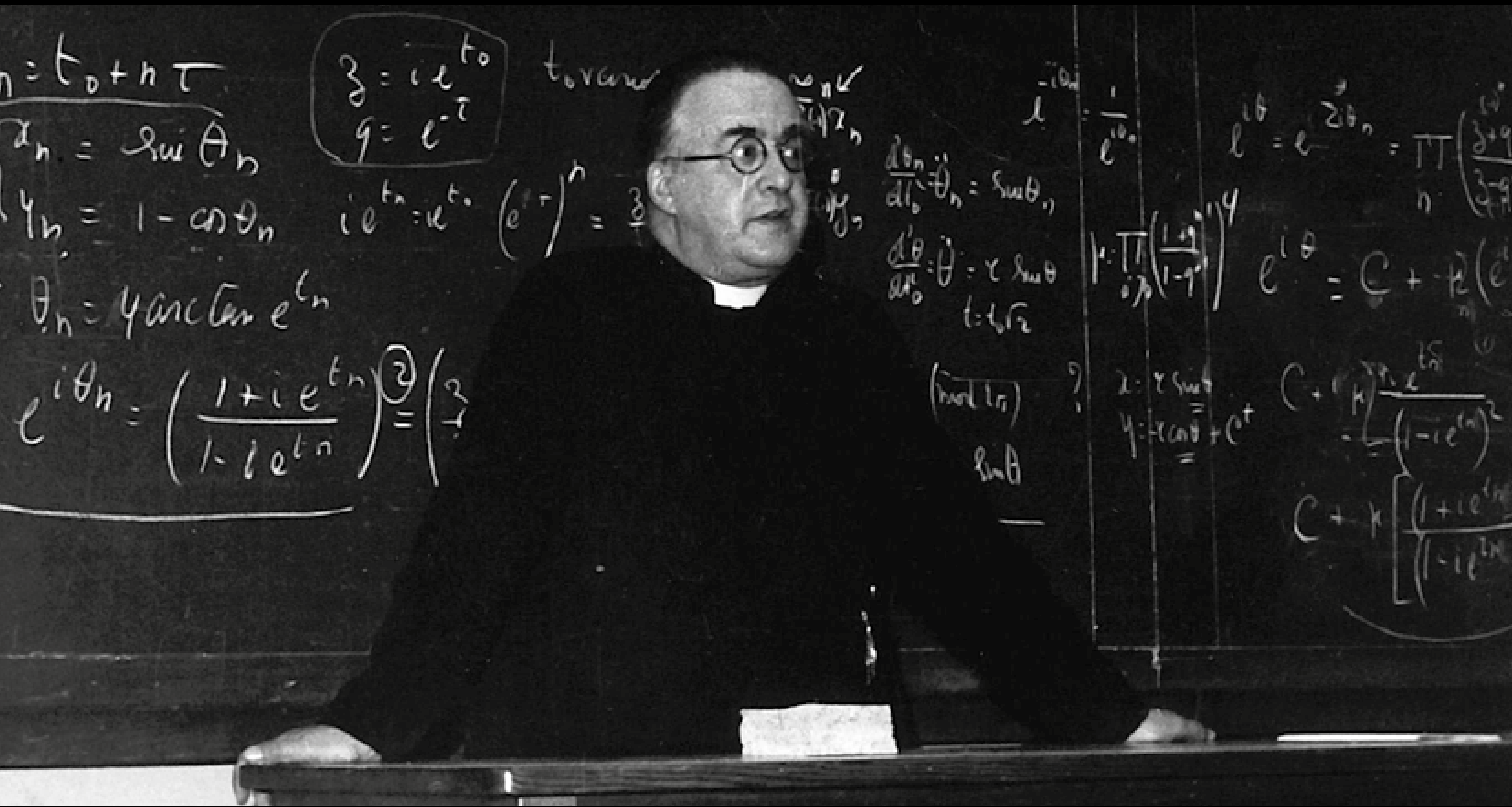
Der VSMP pflegt ständige wie auch gelegentliche Beziehungen zu zahlreichen Organisationen diesseits und jenseits der Landesgrenze, zum VSG und zu den Hochschulen. Im Weiteren fördert er die Teilnahme von Schülerinnen und Schülern an den Internationalen Mathematik- und Physikolympiaden, Mathe-Kaengeru und dem SYPT. Auch arbeitet der VSMP unterstützend bei Forschungsprojekten mit, so ist er aktuell beim Projekt «GESBI Naturwissenschaft ist (auch) Frauensache!» als Transfergruppe tätig. In jüngster Zeit hat der VSMP z.B. bei den Themen «Basale Kompetenzen», «Fach Informatik» und «Revision MAR» mitgewirkt. Dabei konnte er seinen Standpunkt bezüglich gewisser aktueller, politischer und gesellschaftlicher Aspekte im Umfeld der Schule einbringen.

Die SPG und der VSMP - Doppelmitgliedschaft

Die Mitgliedsbeiträge für Doppelmitglieder sind gegenüber den jeweiligen Einzelbeiträgen wie folgt vergünstigt: Ordentliche Mitglieder zahlen in der SPG nur CHF 60.- statt CHF 80.-. Im VSMP beträgt der Mitgliedsbeitrag nur CHF 30.- statt CHF 40.-.

Symposium
125th Anniversary of Georges Lemaître

21 November 2019, Kuppelsaal, Hauptgebäude,
Universität Bern, Hochschulstrasse 4, 3012 Bern



Georges Edouard Lemaître (1894 - 1966) was a Belgian physicist, astronomer, and Roman Catholic priest. He proposed an expanding universe and is the central founding father of the Big Bang model of the Universe.

Afternoon Program
(14:15 - 18:00)

Harry Nussbaumer (ETH Zürich)
Lemaître and the Astronomical Environment of the 1920s

Jean-Pierre Luminet (CNRS Marseille)
Philosophical aspects and implications of Lemaître's contributions to modern cosmology

Norbert Straumann (Universität Zürich)
On Lemaître's inhomogenous cosmological model of 1933 and its recent revival

Evening Program
(19:00 - 20:00)

Friedrich-Karl Thielemann (Universität Basel)
Making the Elements in the Universe: From the Big Bang to Stars and Stellar Explosions

Further information

www.sps.ch
www.scnat.ch

Free entrance, no registration required

⟨S|P|S⟩ swiss physical society

Organisation:
SPS: Claus Beisbart (Claus.Beisbart@philo.unibe.ch)
SCNAT: Marc Türler (marc.tuerler@scnat.ch)

scnat swiss academy of sciences

Ausschreibung der SPG Preise für 2020
Annonce des prix de la SSP pour 2020

Auch im Jahr 2020 sollen wieder SPG Preise, die mit je CHF 5000.- dotiert sind, vergeben werden.

- SPG Preis gestiftet vom *Forschungszentrum ABB Schweiz AG* für eine hervorragende Forschungsarbeit auf **allen Gebieten der Physik**
- SPG Preis gestiftet von der Firma *IBM Research GmbH* für eine hervorragende Forschungsarbeit auf dem **Gebiet der Kondensierten Materie**
- SPG Preis gestiftet von der Firma *Oerlikon Surface Solutions AG* für eine hervorragende Forschungsarbeit auf dem **Gebiet der Angewandten Physik**
- SPG Preis gestiftet vom *Eidgenössischen Institut für Metrologie METAS* für eine hervorragende Forschungsarbeit **mit Bezug zur Metrologie**
- SPG Preis gestiftet von der Firma *COMSOL Multiphysics GmbH* für eine hervorragende Forschungsarbeit auf dem **Gebiet der computergestützten Physik**

Die SPG möchte mit diesen Preisen **junge** Physikerinnen und Physiker in der Frühphase ihrer Karriere, auf alle Fälle vor Erreichen einer akademischen Festanstellung oder bevor sie mehr als drei Jahre in einer Start-up Firma oder in der Industrie tätig sind, für hervorragende wissenschaftliche Arbeiten auszeichnen.
Die eingereichten Arbeiten müssen entweder in der Schweiz oder von SchweizerInnen und Schweizern im Ausland ausgeführt worden sein. Die Beurteilung der Arbeiten erfolgt auf Grund ihrer Bedeutung, Qualität und Originalität.

Der Antrag muss folgende Unterlagen enthalten:
Beschreibung der wissenschaftlichen Arbeit, die prämiert werden soll, inklusive eines wissenschaftlichen Gutachtens. Ein Lebenslauf des Kandidaten, sowie zusätzliche Informationen, die die wissenschaftliche Leistung unterstreichen: Dazu gehören eine Aufstellung der Publikationen in renommierten Zeitschriften und von Einladungen zu Vorträgen, sowie Informationen über eventuell erhaltene Fördermittel, über angemeldete und erteilte Patente, über akademische Preise und Auszeichnungen, etc. Die Relevanz und der Impakt dieser Arbeit in ihrem wissenschaftlichen Gebiet sollen deutlich herausgestrichen werden.

Diese Unterlagen werden elektronisch im "pdf"-Format direkt an das Preiskomitee eingereicht (große Dateien bitte komprimieren (zip)):

En 2020, la SSP attribuera à nouveau des prix de CHF 5000.- chacun, à savoir:

- Le prix SSP offert par le *centre de recherche ABB Schweiz AG* pour un travail de recherche d'une qualité exceptionnelle dans **tout domaine de la physique**
- Le prix SSP offert par l'entreprise *IBM Research GmbH* pour un travail de recherche d'une qualité exceptionnelle en **physique de la matière condensée**
- Le prix SSP offert par l'entreprise *Oerlikon Surface Solutions AG* pour un travail de recherche d'une qualité exceptionnelle dans le **domaine de la physique appliquée**
- Le prix SSP offert par *l'institut national de métrologie de la Suisse METAS* pour un travail de recherche d'une qualité exceptionnelle **faisant référence au domaine de la métrologie**
- Le prix SSP offert par l'entreprise *COMSOL Multiphysics GmbH* pour un travail de recherche d'une qualité exceptionnelle dans le **domaine de la physique numérique**

La SSP distingue avec ces prix des travaux scientifiques exceptionnels de **jeunes** physiciens dans la première étape de leur carrière et qui n'ont pas encore atteint une position permanente universitaire ou qui ne travaillent pas depuis plus de trois ans dans l'industrie. Les travaux soumis doivent avoir été effectuées en Suisse ou par des citoyens Suisses à l'étranger. L'évaluation s'effectue selon des critères d'importance, de qualité et d'originalité du travail soumis à la compétition.

Une nomination complète contient:
Une description du travail scientifique soumis, y compris une lettre de référence. Un curriculum vitae du candidat, ainsi que des informations supplémentaires qui mettent l'accent sur les réalisations scientifiques: notamment une liste de publications dans des revues prestigieuses, des invitations de présenter à des conférences importantes, ainsi que des informations sur des requêtes reçues, des brevets en attentes ou délivrés, des prix ou d'autres distinctions académiques, etc. L'importance et l'impact de ce travail dans son propre domaine scientifique doivent être clairement présentés.

Ces documents seront envoyés électroniquement en format "pdf" directement au comité de prix (svp. comprimez des fichiers très grands (zip):

awards@sps.ch

Einsendeschluss: 31. Januar 2020

Délai: 31 janvier 2020

Die Preise werden an der Jahrestagung 2020 in Fribourg überreicht. Das Preisreglement befindet sich auf *www.sps.ch*.

Les prix seront attribués à la réunion annuelle qui se tiendra en 2020 à Fribourg. Le règlement des prix se trouve sur *www.sps.ch*.