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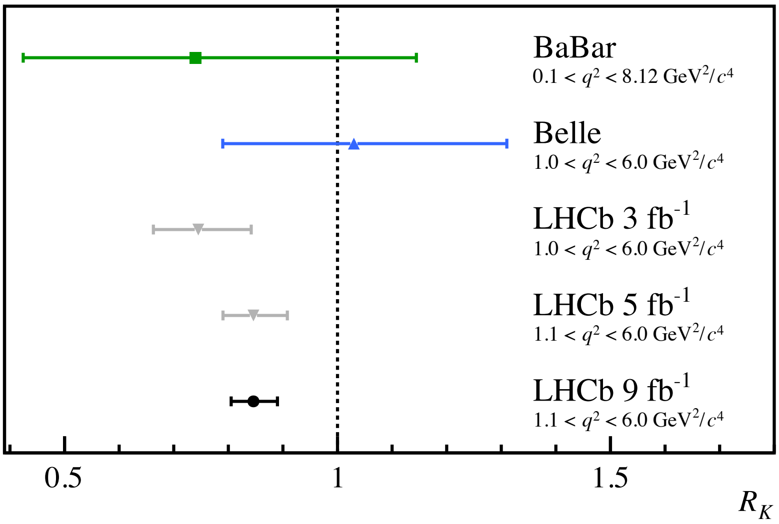
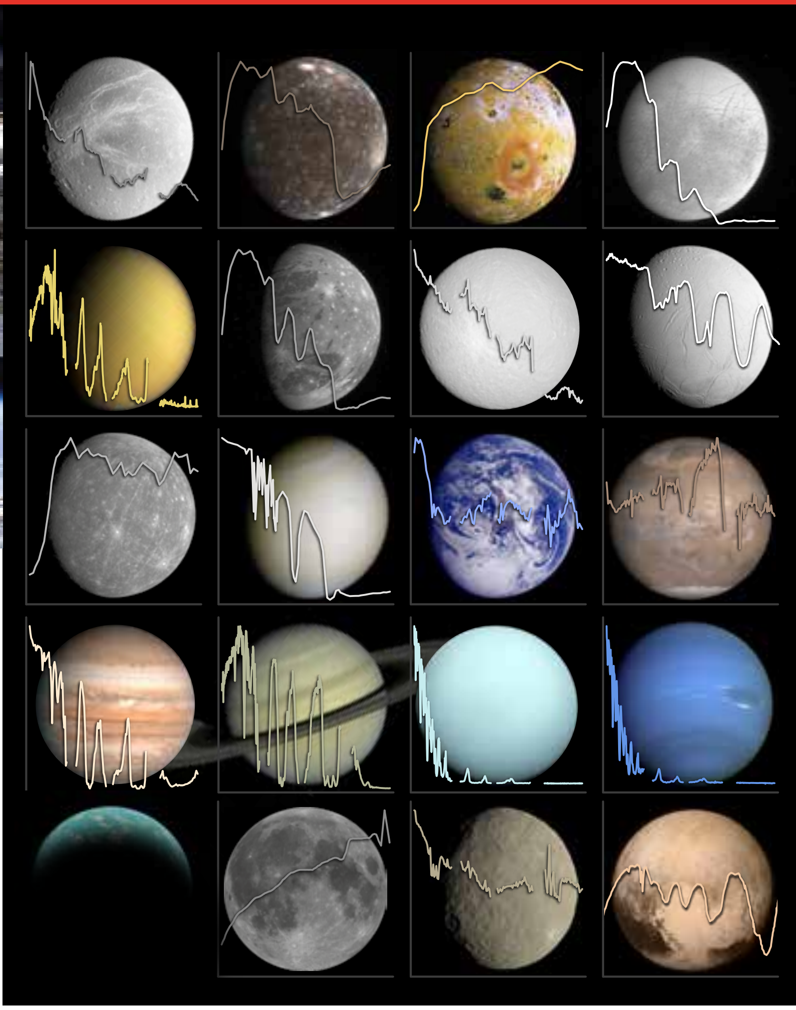


Top: The Alpha Magnetic Spectrometer (AMS-02) is running since 2011 on the International Space Station. More on p. 33.

Middle: Recent experiments confirm flavor anomalies. Details on p. 43.



Top: A spectra catalog of diverse bodies in our solar system helps also to characterise exoplanets (p. 27). (Image credit J. Madden, CSI; see [21] in the article)

Bottom: The winners of the SPS, ÖPG, CHIPP, and Charpak-Ritz awards, together with the societies' presidents, at the Joint Annual Meeting in Innsbruck (p. 4 and 7).

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Prof. Philippe Jetzer, Uni Zürich, jetzer@physik.uzh.ch

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Prof. Guillermo Pedro Acuna, Uni Fribourg, guillermo.acuna@unifr.ch

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Dr. Gernot Scheerer, CERN, gernot.werner.scheerer@cern.ch

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vakant

Biophysik, Weiche Materie und Medizinische Physik - Biophysique, Matière molle et Physique médicale
Prof. Christof Aegerter, Uni Zürich, aegerter@physik.uzh.ch
Dr. Christof Fattinger, christof.fattinger@gmail.com

SPG Administration - Administration de la SSP

Allgemeines Sekretariat - Secrétariat générale
(Mitgliederverwaltung, Webseite, Druck, Versand, Redaktion Bulletin & SPG Mitteilungen) - (Service des membres, internet, impression, envoi, rédaction Bulletin & Communications de la SSP)
S. Albietz, SPG Sekretariat, Departement Physik,
Klingelbergstrasse 82, CH-4056 Basel
Tel. 061 / 207 36 86, Fax 061 / 207 37 84, sps@unibas.ch

Wissenschaftliche Redakteure - Rédacteurs scientifique
Dr. Bernhard Braunecker, braunecker@bluewin.ch
Dr. MER Antoine Pochelon, antoine.pochelon@bluewin.ch
Dr. Margherita Boselli, CERN, margherita.boselli@cern.ch

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Editorial

Physics for Society: Grand Challenges in the Horizon 2050

Hans Peter Beck, SPS Vice President

Physical societies, whether in Switzerland, in Europe, or anywhere in the world share common goals. They all promote the inclusive advancement of physics-based research, they engage with the public by facilitating access to new results in physics, they stimulate the relevance of physics in teaching and school education. Thereby, they unite people and promote the exchange of scientific ideas and make the expertise of their members on physics issues available to decision-makers in politics and industry. All these activities foster the role of physics in society.

But society has needs and the challenges society faces do need answers and guidance – also from physics. Hence, a dialogue between society and physicists is a core issue. The questions need to be translated in actions, therefore the European Physical Society, EPS, has put on its agenda the questions and tasks to define the world's agenda for physics at the horizon 2050. The tasks ahead that need to be mastered at a global scale are huge, especially when sustainability and clean energy provision, climate change and implementing the Paris agreement, health, etc. in a complex and global economy need to be addressed.

Predictions are always difficult but current trends in science and technology indicate what steps need to be taken. International collaboration and interdisciplinary science will play a crucial role to address these grand problems. On 28 - 29 October, 2021, in the Magnus-Haus in Berlin, a jointly organized event by the DPG and the EPS will discuss these questions, where SPS and other physical societies also have contributed [1]. The role of physics for society is manifold and relevant, which becomes evident, when fundamental questions from particle physics or (quantum) gravity are tackled, when quantum many-body systems and the search for new materials is considered, when the interface between physics and biology and the question of what is life is addressed, when physics for health in diagnostics and therapies is taken as granted, etc.

On a slightly smaller scale, but for the very same reasons, SPS launched its new *SPS Focus* series, which was announced in the previous edition of the *SPG Mitteilungen*, Nr. 64. The first *SPS Focus* issue describes energy generation by nuclear methods based on fission, breeding and fusion, has been finalized this summer and distributed in print to its members and in addition to about 300 stake holders in politics and at research institutions in and outside Switzerland [2].

Spontaneous reactions that have arrived were overwhelmingly positive and include a personal invitation by the director general of the ITER fusion project to further exchange and offering a visit of the site in South of France, or the interest of a major US company who is active in energy production, all underline the impact we have generated with this first issue. Especially the physics-based description of fusion, breeding and fusion technologies have been received as useful and necessary, also in view of the urgent questions arising from the climate change and for establishing a CO_2 neutral society. Breeding of thorium and transmutation of existing radioactive waste is no longer a dream, but is taking steps forward, as can be seen with the new site for accelerator driven transmutation of long-lived isotopes MYRRAH in Belgium [3] or the thorium-fuelled nuclear reactor tests, e.g. in China, as reported by Nature News [5].

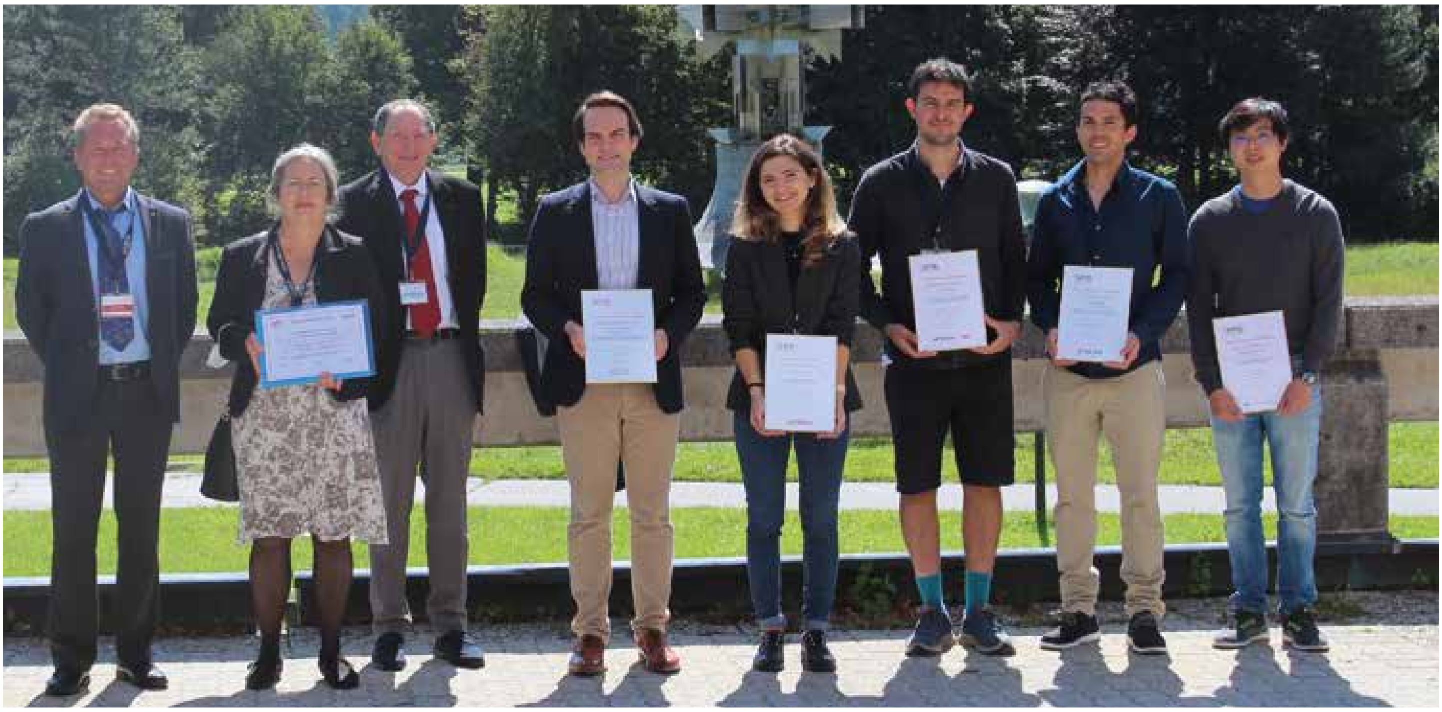
All these reactions and the interest in new large-scale experimental test sites in Belgium, China and elsewhere, confirm and underline the timeliness of the chosen topic of *SPS Focus* No. 1 of the climate problem. *SPS Focus* No. 2 is in preparation and will address the role physics has in Switzerland in society, economics and research.

The challenges society faces on the horizon 2050 are high and physics has a big role when tackling these.

[1] https://www.forumphysicsandsociety.org
[2] https://www.sps.ch/artikel/sps-focus/sps-focus-1
[3] https://www.myrrha.be
[4] https://www.nature.com/articles/d41586-021-02459-w

The winners of the SPS Awards 2021

The SPS Award committee chaired by Prof. Thomas Jung selected the winners for 2021 out of many submissions. The winners presented their work at the Joint Annual Meeting in Innsbruck. Below are the brief summaries directly provided by the winners.



From left to right: Hans Peter Beck, SPS Vice-President; Marie-Emmanuelle Couprie, Winner of the Charpak-Ritz award 2021 (a detailed laudation has already been printed in the SPG Mitteilungen Nr. 64, p. 13); Guy Wormser, SFP President; Niels B. M. Schröter, Clarissa Convertino, Armin Tavakoli, Kristian Cujia, and Kenny Jing Hui Choo, winners of the five SPS Awards.

SPS Award in all Physics Domains, sponsored by Hitachi ABB Power Grids Schweiz

The SPS Award in General Physics is given to **Armin Tavakoli** for his work on "Theory of Quantum Information, in particular Quantum Correlations and Communications".

Quantum correlations and communications

Quantum theory makes predictions of correlations that cannot be explained by classical theories. Recent decades have explored these correlations from several points of view: foundationally understanding quantum theory, quantum information science and its implementation in quantum technologies. This PhD dissertation contributes to aspects of this research program mainly in the following ways.

1) Certification of quantum devices. Simple communication experiments are proposed for certification of a broad fauna of quantum devices subject only small assumptions. Methods are also developed for the strongest form quantum certification targeting high-dimensional quantum measurements.
2) Communication complexity. Quantum correlations can boost the efficiency of communication. This relationship is explored for different types of quantum resources and methods are developed to characterize of quantum advantages. Also, it is proposed to decouple the notion of a quantum bit from the idea of a two-level system. This alternative avenue to informationally restricted correlations is found to qualitatively go beyond traditional qubits.
3) Bell nonlocality in networks. Bell's theorem is a milestone of quantum theory. Recently this research program has expanded into more sophisticated scenarios corresponding to networks. Little is still known about this and several exploratory works into this topic are presented, revealing new types of quantum nonlocality.
4) Autonomous entanglement generation. It is investigated whether strong entanglement can be generated from a thermal machine that only harvests spontaneous environmental interactions. It is found that such minimal machines can probabilistically produce the strongest form of high-dimensional and multi-qubit entanglement.

SPS Award in Condensed Matter Physics, sponsored by IBM

Niels B. M. Schröter received the SPS Award in Condensed Matter Physics for his work on "Groundbreaking discovery and further investigation of new multifold fermions in chiral topological semimetals".

New fermions with large topological charges in chiral topological semimetals

Chiral topological semimetals are a new class of topological matter that host chiral multifold fermions in a chiral crystal structure. These new fermionic quasiparticles can be viewed as a higher spin generalization of Weyl fermions without equivalence in elementary particle physics. Their large topological charge has been predicted to give rise to unusual phenomena, such as giant quantized photocurrents, long fermi-arc surface states, unusual magnetotransport signatures, new spin-orbit torques, or unconventional and topological superconductivity. Whilst there have been many theoretical predictions related to multifold fermions in previous years, they have so far remained elusive in experiments.

Here I will report the experimental observation of multifold fermions in a chiral topological semimetal. Using angle-resolved photoelectron spectroscopy, we directly visualize their long fermi-arc surface states and resolve a band splitting that indicates that they carry the largest topological charge that can be realized for quasiparticles in any material. We are also able to show experimentally that there is a direct relationship between the handedness of the crystal structure and the electronic chirality (i.e. the Chern number sign) of the multifold fermions, which indicates that structural chirality can be used as a control parameter to manipulate phenomena that are sensitive to the electronic chirality, such as the direction of topological photocurrents. I will then also present our latest experimental results about new directions in the field of chiral topological semimetals.

[1] N. B. M. Schröter et al., Nat. Phys. **15**, 759–765 (2019).
[2] N. B. M. Schröter et al., Science **369**, 179 (2020).

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

The SPS Award in Applied Physics is given to **Clarissa Convertino** for her work on "Development of an advanced hybrid MOSFET/ tunnel FET platform".

Development of an advanced hybrid MOSFET/tunnel FET platform

High power consumption represents a major bottleneck for conventional transistor technologies (MOSFETs), due to the inability of further reducing supply voltage while simultaneously limiting the off-state leakage current. This limitation can be overcome by Tunnel FETs, a novel transistor concept based on the quantum-mechanical band-to-band tunneling, but the best TFET demonstrators so far are based on vertical nanowire approaches which are not compatible with advanced IC technology. During my PhD research, I demonstrated the first hybrid technology platform combining III-V Tunnel FETs and MOSFETs with a scalable process and suitable for large-scale semiconductor manufacturing [1]. Such low-power technology platform paves the way to future energy efficient electronics, with the ultimate goal to reduce the carbon footprint of the ICT industry. The demonstrated platform exploits the synergies between the world of Tunnel FETs and of III-V MOSFETs [2], as it allows to implement hybrid logic blocks tailored to the unique specifics of each device. Tunnel FETs provide lower leakage and good performance at low voltages levels, MOSFETs are faster (at same dimension and bias) and provide greater current drive. The developed fabrication flow is identical for both devices except for a single masking and epitaxy step, opening up for manufacturing of truly hybrid logic blocks. Unlike a MOSFET, the TFET is an asymmetric device with different materials in the source and drain regions. Key to achieving the reported performance is the invention of a selective source approach, where the GaAsSb source is grown right before the replacement gate process, resulting in self-alignment of the gate. The fabricated TFETs show a subthreshold swing of 47 mV/decade, outperforming the state-of-the-art with a superior device platform and unmatched scaled device dimensions.

[1] C. Convertino et al., “Hybrid III-V tunnel FET and MOSFET technology platform integrated on silicon,” Nature Electronics (2021). https://doi.org/10.1038/s41928-020-00531-3
[2] C. Convertino et al., “InGaAs-on-Insulator FinFETs with Reduced Off-Current and Record Performance,” in IEEE International Electron Devices Meeting (IEDM), pp. 39.2.1-39.2.4, 2018. https://ieeexplore.ieee.org/document/8614640

SPS Award related to Metrology, sponsored by METAS

Kristian Cujia is honored with the SPS Award related to Metrology for his work on "Outstanding research in quantum sensing and quantum metrology with nitrogen vacancies".

Discrete-time signal processing with NV centers

In 1950, Erwin L. Hahn reported a seminal experiment on detecting the oscillating magnetization of atomic nuclei following excitation by a short burst of radio-frequency radiation. This so-called “free induction decay” (FID) signal initiated the field of modern NMR spectroscopy, which has become a standard tool in chemical analytics and medical MRI tomography.

While NMR and MRI operate on large sample volumes (including humans), it has been unclear from a basic physics standpoint whether FID detection can be extended down to a *single* nuclear spin, or whether this is inhibited by the laws of quantum mechanics. Until recently, this question has been mainly theoretical, because the magnetic signals of single nuclear spins have been far too week for existing magnetic detectors. However, recent advances with quantum defect spins in diamond, most notably the nitrogen-vacancy (NV) center, have brought single nuclear spin detection within reach.

NV centers are atomic-scale defects that are sensitive, among others, to external magnetic fields via dipolar interactions. In recent years, they have attracted considerable attention for their potential as highly sensitive magnetic probes. Owing to their inherent quantum nature, they are extremely sensitive to perturbations, and thanks to their atomic-scale size they can be brought in very close proximity to a target.

In our work, we used a spectroscopy method based on sequential weak measurements (also known as quantum non-demolition measurements) to detect the FID signal of a single carbon-13 nuclear spin [1]. We showed that such measurements mitigate the unwanted quantum back-action, and provide a number of further advantages, including a large frequency bandwidth and possibility of efficient Fourier NMR methods. Building on this experiment, we further showed that single nuclear spin NMR can be extended to image large nuclear spin clusters with three-dimensional atomic resolution. As a proof-of-principle, we demonstrated the detection of up to 29 carbon-13 nuclear spins in diamond, and showed how, by applying information-criteria principles to the detected signals, the three-dimensional atomic positions of nuclei in the diamond lattice can be recovered [2]. Next steps include functionalizing diamond surfaces with single target molecules (like proteins) and to apply the single-spin NMR techniques to structural imaging and monitoring of chemical surface reactions.

[1] K. S. Cujia, J. M. Boss, K. Herb, J. Zopes and C. L. Degen. Tracking the precession of single nuclear spins by weak measurements. Nature **571**, 230 - 233 (2019).
[2] K. S. Cujia, K. Herb, J. Zopes, J. M. Abendroth and C. L. Degen. Parallel detection and spatial mapping of large nuclear-spin clusters in diamond. arXiv:2103.10669 (2021).

SPS Award in Computational Physics, sponsored by COMSOL Multiphysics GmbH

The SPS Award in Computational Physics is given to **Kenny Jing Hui Choo** for his work on "Novel computational approach to solve quantum many-body problems".

Neural Network Quantum States

Over the past few years, Artificial neural networks (ANN) have led to numerous breakthroughs from improving language translations to beating the best players in Chess and Go. In the field of condensed matter physics, ANNs have also been recently introduced as a general ansatz known as neural network quantum states (NQS) to represent many-body wavefunctions. In conjunction with variational Monte Carlo calculations, this ansatz has been applied to find Hamiltonian ground states and their energies [1]. We have extended upon this approach to study excited states, a central task in several many-body quantum calculations. By using a Gram-Schmidt type orthogonalisation procedure, we were able to obtain the first excited state of a system. In addition, by incorporating spatial symmetries further spectral properties could be addressed.

Furthermore, we have also applied the methods developed to the J1-J2 model on the square lattice [2]. Using deep convolutional networks, we showed that the NQS are able to achieve competitive results with respect to other state-of-the-art approaches such as density matrix renormalisation group, across the full phase diagram.

[1] K. Choo et al. “Symmetries and Many-Body Excitations with Neural-Network Quantum States“, Phys. Rev. Lett. **121**, 167204 (2018)
[2] K. Choo et al. “Two-dimensional frustrated J1-J2 model studied with neural network quantum states”, Phys. Rev. B **100**, 125124 (2019)

Review of the Joint Annual Meeting 2021 in Innsbruck

The Joint Annual Meeting of the Austrian and Swiss Physical Societies marked for many of us the first on-site conference since the outbreak of the COVID-19 pandemic. By all measures, this conference – held in the beautiful environment of Innsbruck – was a success and I would like to thank both the Swiss and Austrian organizers. The meeting had nearly 600 participants – about 20% more than usual. Health safety measures installed by the university had been well accepted and did not compromise the atmosphere of the event.

With this many participants, the plenary talks had necessitated in all cases video transmission to neighboring auditoriums. The plenary program was well mixed with a variety of topics, presented by renowned speakers. A selection of "extended abstracts", provided by the speakers, can be found on p. 14 of this issue.
In total, more than 320 talks have been presented. Reviews of selected topical sessions are given below.

To me, the vibrant poster sessions with about 100 contributions also illustrated the success of the meeting. Finding the best poster contributions was two-fold challenging. All students had made excellent efforts and to choose one poster over the other was difficult. The other challenge faced by the jury members was to get near the posters. The poster session was packed with people. Countless interactions and discussions took place during these sessions. The winners of the Best Poster Awards are presented on p. 12.

The Technik Campus

Next year, the annual meeting of the Swiss Physical Society will be held in Fribourg from 27 - 30 June – reserve these dates. My hope is that over time we can grow this meeting. As seen in Innsbruck, more participants animate the conference. Therefore, please encourage your colleague physicists to join the 2022 annual meeting. To cultivate higher participation in the SPS meetings also makes sense in a more global effort to adapt the goals set by the Paris agreement. To limit human contribution to global warming we scientists have a responsibility to reduce our greenhouse gas emission footprint. A way forward is to gradually reduce or at least change the format of intercontinental conferences. Supporting local and regional meetings is one way to generate more sustainable scientific exchange.

Johan Chang, SPS President

History and Philosophy of Physics

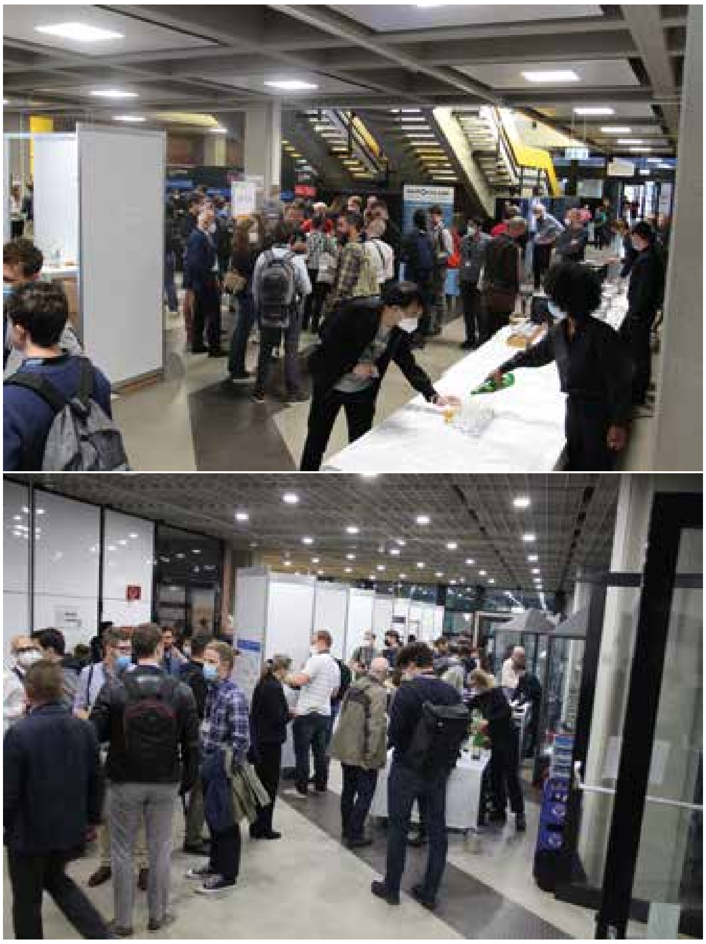
The History and Philosophy of Physics session was organized by members of the Austrian Physical Society and featured four interesting talks. Michael C. F. Wiescher (University of Notre Dame, USA), gave an excellent paper co-authored with Wolfgang L. Reiter and Walter Kutschera. The focus was on Arthur E. Haas, one of the last students of Ludwig Boltzmann. He deduced a correct correlation between the Planck constant and the “Bohr” radius already in 1910. But the leading Viennese physicists took this to be a “carnival joke” or confusion. Franz Sachslehner (University of Vienna) presented a Rowland concave diffraction grating from 1895 produced by H. A. Rowland’s ruling engine and used by Franz Serafin Exner and Eduard Haschek around 1900. This grating and other spectroscopic devices of Exner’s time have been tested experimentally with quite good results. Heinz Krenn (University of Graz) discussed Boltzmann’s H-theorem and the interpretation of thermodynamic and informational entropy. The thought experiment by L. Szilard, Landauer’s, Shannon’s measure of information and J. von Neumann’s entropy, also called “negentropy”, were presented. Finally, Reinhard Folk (Johannes Kepler University Linz) commented on the development of the Ising model, which is crucial to the understanding of ferromagnetism. Here, the progress of quantum mechanics due to Pauli and Heisenberg was significant.

Franz Sachslehner

Condensed Matter

This year, the field of condensed matter saw many exciting topics such as device physics, magnetism, superconductivity, topology and quantum phases over seven oral and two

The plenary speakers in Innsbruck: Ulrike Diebold, Luciano Rezzolla, Hugo Zbinden, Brigitte Bach, ...



Coffee breaks and poster sessions were well frequented.

poster sessions. Both new and more classical topics were represented. In this fashion, new results were reported on magic angle graphene and metallic Kagome systems. On more classical topics, a new crystal structure of ice was reported and a bold theoretical proposal for high temperature p-wave superconductivity was put forward. Naturally, aspects of topology – quasi-particle identification, phase transition classification and anomalous electronic transport – were discussed. On magnetism, newest results on skyrmions and interdisciplinarity to social science were covered.

Johan Chang

Surfaces, Interfaces and Thin Films

Five sessions dedicated to surfaces, interfaces and thin films took place during the meeting, with many excellent talks. There was a great increase in the number of contributed talks from the previous joint annual meeting, which hosted only two sessions in this area. The majority of talks reported recent progress on metal-oxides (Fe_2O_3, Fe_3O_4, TiO_2, In_2O_3, and $SrTiO_3$, to name a few). However, other fields, such as 2D materials, were also represented by several excellent talks followed by a fruitful discussion. Alongside the experimental results, two talks from Prof. Diebold's group presented a recent instrumental development at TU Wien, covering the low-energy electron diffraction I(V) spectroscopy and infrared reflection absorption spectroscopy to investigate structure and adsorbates on metal-oxide single crystals.

Zbynek Novotny

TASK - FAKT

This year, the “Kern-, Teilchen- und Astrophysik” (TASK) session was organized jointly with the corresponding FAKT (Fachausschuss für Kern- und Teilchenphysik) 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 78 talks and 8 posters organised in seven topical sessions covering high energy physics, dark matter and neutrino physics, astroparticle physics as well as high precision low energy physics. 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. A particular emphasis was given to discussing the latest “Flavour Anomalies” reported by LHCb and putting these in context to other recent measurements

Gabriel Cuomo, winner of the CHIPP Award, with Rainer Wallny, Chair of the CHIPP Executive Board.

... Lisa Kaltenegger, Hans Peter Beck, Martina Merz, Michael Benedikt, ...

and theory predictions. A plenary review talk on the subject by Patrick Owen on Thursday morning was also well received (see the article in our *Progress in Physics* series on p. 43). The CHIPP prize for the best PhD thesis work in particle physics in 2021 was given to Gabriel Cuomo. The CHIPP Prize jury honours Gabriel for his outstanding theoretical studies of quantum field theories in the strongly coupled regime, which elucidated new properties relevant to a wide range of physical systems: from condensed matter to cosmology. All slides presented at the TASK sessions are available from the conference page under *https://indico.cern.ch/event/1015032/timetable/*.

Andreas Schopper

Physics in Industry: “Start-ups – From great physics to innovative products”

This year’s edition of the “Physics in Industry” session was focused on physics-based start-ups, which play a key role in bringing ideas from the lab to the market. The presentations from nine spin-off companies from Austria and Switzerland were complemented by one from the technology transfer office of the University of Innsbruck. They all showcased fascinating stories in various sectors and covered the different phases after founding and the concomitantly evolving challenges. Interested graduates could get a very good sense about the “dos” and “don’ts” in the process of founding a company and what entrepreneurship entails, but also how exciting it can be to be part of a start-up. A more detailed account of the inspiring talks is given in a dedicated article in the “Physicists in Industry” section of this issue (p. 53).

Thilo Stöferle

Biophysics, Medical Physics and Soft Matter

Two sessions on Biophysics, Medical Physics and soft matter were held on Tuesday 31 August with two invited presentations and 7 contributed talks. The talks covered a wide range of topics all through the different fields, with two talks focusing on improving current computer tomography technology in medical imaging, as well as one on the development of highly efficient biosensors. In Biophysics, there were two talks describing different possibilities of applying and measuring forces in microorganisms and developing tissues as well as one concerning the communication strategies of honey bees in response to a predator. Finally, soft matter was covered in the study of multiply scattered waves in disordered media, ranging from coherent backscattering in acoustic waves to the use of satellite data to create UV maps and special modes of scattered waves that are invariant under disordered media.

The conference dinner took place in the "Villa Blanka". Located up-town, the participants enjoyed therefore besides an apéro and excellent meals also an exciting view on the city.

... Kevin Heng, Anandhan Danasingh (substitute for Ingeborg Hochmair), Peter Ullrich, Arnold Hanslmeier.

Hanns-Christoph Nägerl (right), local organiser of the Joint Annual Meeting, together with the two presidents, during his "After Dinner Speech" at the Villa Blanka.

On the side of biosensors, Andreas Frutiger (lino Biotech AG) demonstrated how spatial lock-in techniques can be used to dramatically increase the efficiency of biosensors due to the efficient suppression of noise and drifts. This spatial lock-in becomes possible due to the regular patterning of the sensor molecules in a spatially ordered pattern concurrent with observation using diffracted light at similar length scales.

In the second session, Stefan Rotter (TU Wien) showed that certain states of light modulation can be transported in disordered media without being altered. While these are particular for the disordered media in question, these may nevertheless be used to enhance imaging in disordered media as small changes due to object to be imaged can be uncovered from changes to such states.

Christof, Aegerter, Christof Fattinger

Education and Promotion of Physics

The joint session “Physik und Schule & Young minds”, co-organised with Alexander Strahl, head of the section Physics and School of the Austrian Physical Society, was a great success, despite the exceptional circumstances of the pandemic. With about 25 participants, there was a cheerful atmosphere in the auditorium and lively discussions around the presentations.

Contributions covered a broad range of topics: from the talk by the laureate of the Sexl award for physics education, Ilse Bartosch (Uni Vienna), providing an elaborate overview about sustainable development and its important role in physics education; through development of high quality learning and teaching materials for particle physics (Barbora Bruant Gulejova, IPPOG/International Particle Physics Outreach Group and Uni Bern); to physics education research on digital competencies of physics teachers, a topic of high current interest (Lars-Jochen Thoms, Teacher Education Uni Thurgau and Uni Konstanz).

Moreover, the Physics Olympiads and the International Young Physicists' Tournament were presented, and there were talks by the awardees of the ÖPG Matura thesis award and by the awardees of the Students' Award of the ÖPG/ Young Minds especially for an audience of pupils and teachers. The quality of the work done by the awardees and of the presentations was truly impressive. The format of this special session by our Austrian colleagues appears as very promising also for future educational activities by the SPS.

As a further highlight of the conference related to physics education was the talk “Physics & Education - Perspectives from Particle Physics” by Hans Peter Beck (CERN, Uni Bern and Fribourg), who succeeded in an excellent way to show the importance of particle physics for the modern scientific worldview and other educational and societal aspects (p. 22). Similar presentations for other areas of physics would be a most valuable way to promote physics at school.

Andreas Müller, Gernot Werner Scheerer

Theory

Since few years at the annual meeting of the SPS theoretical contributions are presented in their respective topical sessions and no longer in a dedicated theory session.
This has been quite successful and well appreciated. This year in Innsbruck there were about 78 theoretical talks distributed in the respective sections: in the TASK-FAKT sessions there were 16 theory related presentations, of which six talks were part of the "Flavor Anomalies" session, five related more generally to High Energy Physics, whilst the other five presentations were scheduled in the Astroparticle, Dark Matter and Atomic Physics sessions. In the Biophysics, Medical Physics and Soft Matter sessions there was only one theory talk (out of 17 contributions). The KOND sessions included some 20 theory talks (out of more than 80 contributions) with topics ranging from spin phenomena, topological systems and quantum phenomena to phases of matter. In the Atomic Physics and Quantum Optics sessions some 8 talks out of almost 40 were theoretical ones. The number of theory talks varies significantly among the various sections, which is of course not surprising as each one has their own traditions. However, from the above quoted numbers it emerges that the theory talks are in general a sizeable fraction (~ 15 - 30 %) of all contributions.

Philippe Jetzer

New SPS committee members

Prof. Dr. Ilaria Zardo
(Section KOND)

Ilaria Zardo received her diploma in Physics from the Università degli Studi di Roma "Sapienza" in 2007. In 2010, she received her Ph.D. in Physics from the Technische Universität München and Università di Roma "Sapienza" with summa cum laude. From 2010 to 2011, she was a postdoc in the group of Gerhard Abstreiter at Technische Universität München and from 2012 to 2015 in the group of Erik Bakkers at the Technical University of Eindhoven. In 2014, she was awarded with the Innovational Research Incentives Scheme Veni, which is a prestigious Talent Scheme of the Netherlands Organisation for Scientific Research (NWO), meant for talented, creative researchers who are starting their own line of research. She received in 2015 the Hertha-Sponer Prize, awarded to a female scientist for outstanding scientific work in the field of physics. In 2017, she has received the prestigious Starting Grant of the European Research Council (ERC). She was appointed as a tenure track assistant professor at the Department of Physics at the University of Basel in 2015 and became a tenured Associate Professor in 2020.

Her research focus lies in Nanophononics: the design and manipulation of the phononic properties of materials at the nanoscale. To reach this goal, her group works on the development of novel materials as well as on the development of novel measurements platforms and the further advancement of existing experimental techniques. This approach enables them to elaborate new materials and innovative solutions for small sensors and energy harvesting.

As she is already very active in outreach initiatives, also in participating to activities promoted by the Swiss Academy of Engineering Sciences (SATW), she would like to further contribute to the Swiss Physical Society outreach activities, promoting science and young female researchers.

Prof. Dr. Jean-Philippe Brantut
(Section Atomic Physics and Quantum Optics)

Jean-Philippe Brantut is assistant professor of Physics at EPFL. He did in PhD at the Institut d'Optique in Palaiseau, under the direction of Philippe Bouyer, in the group of Alain Aspect. He then worked at ETH Zürich first as Post-doc from 2010 to 2013, then as Ambizione fellow in the group of Tilman Esslinger, before moving to EPFL in September 2016 as the Fondation Sandoz chair in physics of quantum gases.
His research is focused quantum gases, in particular the integration of interacting, ultra-cold atoms in mesoscopic or quantum-optical devices and structures. At EPFL, his group uses cavity quantum-electrodynamics techniques to explore the physics of strongly correlated matter.

Prof. Dr. Johan Chang has been elected in his new function as SPS President. His presentation has already been printed in the *SPG Mitteilungen* Nr. 62, p. 6.

Best Poster Award 2021

The three best posters presented at the 2021 joint annual meeting of ÖPG and SPS at the University of Innsbruck have been honored with the Best Poster Award, each doted with EUR 200.-. A total of 59 posters competed for the award from which the poster jury selected the works of **Barbora Budinská**, **Michael Denner** and **Franziska Strasser** as the final winners in a two-step evaluation procedure.

A fourth award (also doted with EUR 200.-), sponsored by the *SFB BeyondC*, who co-organised the session on "Quantum Information and Quantum Computing", has been given to **Martin Johannes Renner**.

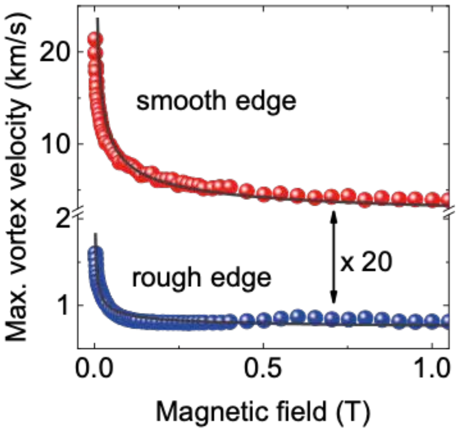
Maurizio Musso, ÖPG President, and the winners Barbora Budinská, Martin Johannes Renner, Franziska Strasser and Michael Denner.

The winners conveyed the essence of their work in a brief 1-slide presentation during the poster award ceremony on the last day of the meeting. We thank the participants for the high quality of their contributions and express our gratitude to all members of the poster jury for their hard work during the evaluation of the posters. Namely, the jury members were: Siham Benhabib, Johan Chang, Lukas Gallmann, Dirk Hegemann, Wolfgang Lucha, Mathias Scheurer and Gottfried Strasser.

Ultra-fast vortex motion discovered in MoSi thin films

Barbora Budinská et al., SuperSpinLab, University of Vienna

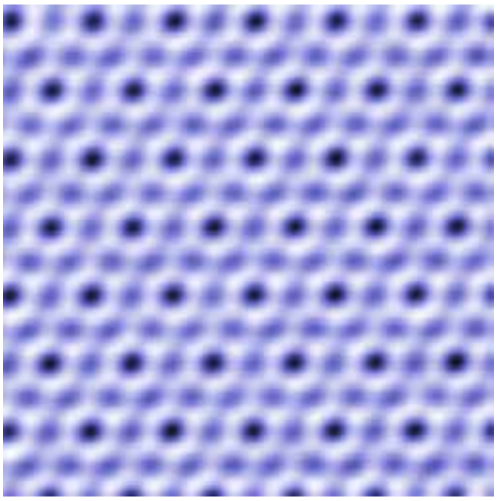
The nonequilibrium processes and fast vortex motion cause the breakdown of superconductivity at large transport currents and determine the performance of superconducting single-photon detectors (SSPDs). However, the primary figure of merit – quasiparticles relaxation time – deduced from electrical voltage measurements does not always reflect an intrinsic property, because of sample's non-uniformity [*https://doi.org/10.1038/s41467-020-16987-y*]. Here, we investigate the effect of the edge quality on the maximal vortex velocities in MoSi thin films. In particular, for a strip with a close-to-perfect edge milled by focused ion beam we realize vortex velocities exceeding 20 km/s and deduce relaxation times on the 20 ps time scale, perfectly in-line with those in state-of-the-art MoSi SSPDs.



Quantum triology in charge ordered kagome superconductors

Michael Denner et al., University of Zurich

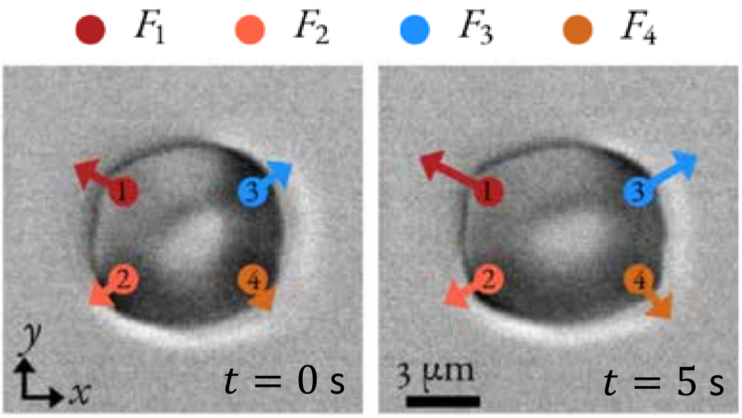
The intertwining of lattice geometry, competing orders, and electronic topology is at the forefront of condensed matter research. Such a quantum triology has recently been discussed in the novel kagome superconductors AV_3Sb_5 (A = K, Cs, Rb). In the work presented in this poster, we demonstrate that the van Hove singularities originating from the kagome lattice give rise to an unconventional charge order, exhibiting dual electronic and magnetic anomalies. The charge order further interweaves with a tantalising unconventional superconducting phase. This triology in kagome superconductors is inspiring manifold experimental and theoretical advances, establishing AV_3Sb_5 as a platform for correlated quantum phases of great promise.
More information: *https://linkmix.co/6167571*.



Direct holographic measurement of torque and individual forces with optical tweezers

Franziska Strasser, Medizinische Universität Innsbruck

Optical tweezers are a powerful tool for measuring tiny forces on the microscale. However, when multiple traps are used, it is challenging to simultaneously measure the individual forces and torques. We have addressed this problem with our novel holographic force measurement method that allows us to recover the individual forces from a single farfield interference image. As this method does not require information about size, shape, or optical properties of the particle it is well suited to study biological specimen. We demonstrate measurements for up to ten traps, and disentangle the individual forces on a red blood cell stretched by four optical traps (see figure). For more information please visit: https://www.i-med.ac.at/dpmp/bmp/

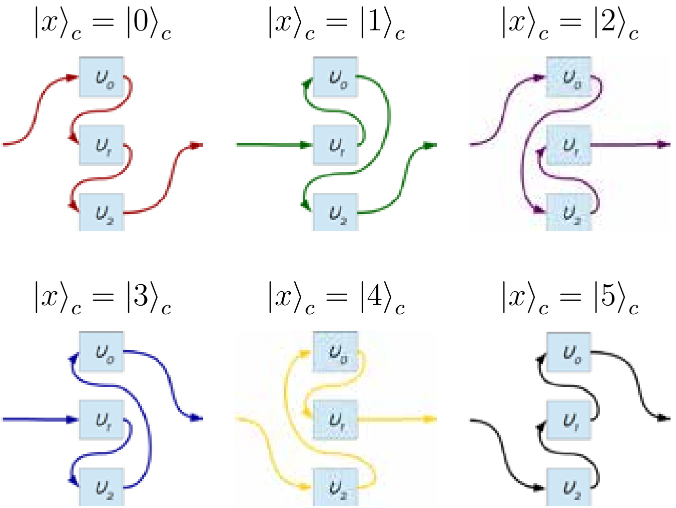


Recovered individual forces (arrows) applied to a red blood cell stretched with four optical traps.

Reassessing the computational advantage of quantum-controlled ordering of gates

Martin J. Renner et al., University of Vienna

In an ordinary quantum algorithm, represented within the quantum circuit model, the quantum gates are always applied in a fixed order on the systems. The use of indefinite causal structures allows to relax this constraint and apply the gates in a superposition of different orderings. It was expected that this new resource can solve certain tasks more efficiently than any ordinary quantum algorithm. However, in our work, we present fixed-order quantum algorithms that can solve the same tasks almost as efficiently as an algorithm that applies the gates in a superposition of different orderings. This raises the important challenge of finding computational tasks for which indefinite causal structures provide a more significant advantage than this one.
See also: https://arxiv.org/abs/2102.11293



Indefinite causal structures: An additional quantum system determines the gate ordering.

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/).

(Note: For editorial reasons the order of the articles does not reflect the order in which the talks were held at the conference.)

PT 1/2021

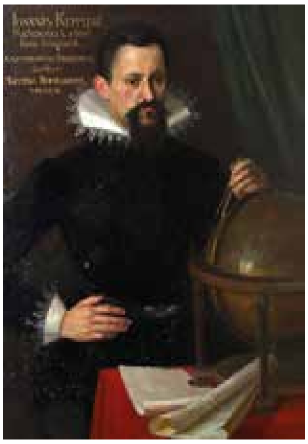
Kepler, Brahe, and Bürgi: To measure and calculate the celestial bodies

Peter Ullrich
Universität Koblenz-Landau, Campus Koblenz, Fachbereich 3: Mathematik/Naturwissenschaften, Mathematisches Institut

Johannes Kepler and his three laws of planetary motion

Even if Kepler's date of birth, December 27, 1571, is given according to the Julian calendar, one can celebrate its 450th anniversary in 2021 since the Gregorian calendar was only introduced in 1582.

After his studies in theology, astronomy, and mathematics at the University at Tübingen, Kepler received a teaching position at the Protestant "Stiftsschule" at Graz in 1594. In reaction to his book *Mysterium cosmographicum* of 1597 Tycho Brahe (1546–1601) offered him a position at Prague to analyze Brahe's astronomical observation data. Kepler followed this offer in 1600 and even became Brahe's successor as Imperial court mathematician to Emperor Rudolf II (1552–1612). The latter hired him for setting up the *Tabulae Rudolphinae*, a collection of tables of positions of celestial objects and rules which made it possible to calculate such positions in advance. [1]



Johannes Kepler,
at the latest in 1620

As a by-product of this Kepler found his laws of planetary motion:

1. **The orbit of a planet is an ellipse with Sun at one of the two foci.**
   (Kepler stated this in his *Astronomia nova* of 1609 only for Mars and without the information on the focus and in his *Epitome Astronomiae Copernicanae* of 1622 in full for all planets of the Solar system.)
2. **The line segment joining a planet and Sun sweeps out equal areas during equal intervals of time.**
   (This is stated in *Astronomia nova* only for Mars and in *Epitome Astronomiae Copernicanae* in general.)
3. **The square of a planet's orbital period is proportional to the cube of the length of the semi-major axis of its orbit.**
   (This is given in Kepler's *Harmonices Mundi* of 1619.)

Even if these laws were found for objects close to Earth, they can be used to detect extra solar planets and measure masses, in particular "dark masses" which cannot be detected elsewise.

After the death of Rudolf II in 1612 Kepler left Prague to become "Landschaftsmathematiker" for Upper Austria at Linz. During the years he got problems with both Christian churches so that he had to escape the town in 1626. But he was able to rescue the manuscript of the *Tabulae Rudolphinae* which were printed in Ulm next year.

That year he also became astrologer to Albrecht von Wallenstein (1583–1634). Kepler died on November 15, 1630 at Regensburg where he wanted to use the "Reichstag" meeting in order to collect outstanding debts.

The general background

At that time the question whether the system of the planets and Sun was geocentric – all celestial objects rotate around Earth – or heliocentric – all around Sun – had been fueled by Nicolaus Copernicus' (1473–1543) book *De revolutionibus orbium coelestium*. So, astronomy had become interesting also for princes. Rudolf II, for example, Emperor of the Holy Roman Empire of German Nation, called Brahe to his capital Prague. Brahe, as already mentioned, in turn called Kepler, not in order to find ellipses but to back up Brahe's own idea for the planetary system which had no ellipses and was not even a true Copernican system.

Even if the Imperial family was not too happy with the interests of Rudolf II in the arts and sciences, astronomy could also be a way to get recognition as a prince, like for Landgrave Wilhelm IV of Hessen-Kassel (1532–1592), who got things going decades before Kepler: Around 1560 he himself started astronomical observations and founded the first fixed observatory in state hands in Europe in modern times. Following Brahe's visit at Kassel in 1575 Wilhelm IV wrote a letter of recommendation to King Frederick II (1534–1588) of Denmark and Norway. In the wake of this, Brahe received the island of Hven in the Öresund as fiefdom and the financial means for his astronomical observatories, which amounted between 1 and 2 percent of the king's revenues.

These activities were not only successful as a scientific but also as a political enterprise: A lot of the influence of the house of Hessen had been gambled away by the father of Wilhelm IV. The scientific activities, however, raised his prestige among the princes, and the astronomical clocks and globes produced at Kassel interested Emperor Rudolf II.

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[1] Note that another Kepler portrait has recently been questioned, see Physics Today **74**(9), 10 (2021). Also Kepler's bust in the Bavarian Walhalla shows a (further) wrong person.

Jost Bürgi

In this respect Bürgi was of utmost importance: He had been born on February 28, 1552 at Lichtensteig, now: Canton St. Gallen, Switzerland, and was trained as watchmaker, but had neither command of Greek nor Latin. When he started to design scientific instruments and astronomical clocks at Kassel on July 25, 1579, his craftsmanship was already excellent: He improved the instruments so that the accuracy of the measurements became comparable to those at Brahe's observatories [2].

Jost Bürgi in 1619

In order to improve his skills, Bürgi read scientific texts written in German and exchanged his knowledge with other astronomers and mathematicians, often in a kind of barter. For example, he helped Nicolaus Reimers Ursus (1551–1600) with mathematics and in turn the latter made the first translation of Copernicus' *De revolutionibus* into German for him. Even with Kepler Bürgi made such a bargain.

By this Bürgi was no longer forced to treat positions of celestial objects as static but could also calculate and then simulate their motion. Before him, celestial globes had mainly been storages for astronomical data. By putting clockworks into such a globe and connecting them with pointers on its surface, however, Bürgi built machines which dynamically showed the position of celestial bodies: The storage had become an analog computer, for example, the "Himmelglobus" of 1594 kept in the Schweizerische Landesmuseum at Zürich.

Simply reading off positions from these simulation devices made them attractive for persons that disliked to bother with calculations. Emperor Rudolf II got interested in them and Bürgi had several audiences with him at Prague. In turn, when Wilhelm IV died, his successor renewed the contract with Bürgi. In 1604, however he moved to Prague for the same position that he had held at Kassel and that he hold under Rudolf II and his two successors.

So Bürgi and Kepler worked together at the Imperial court from 1604 to 1612 when the latter left for Linz. This does not mean, however, that Bürgi was subordinate to Kepler as is sometimes claimed: He had a better salary than Kepler, and on February 3, 1611 he was ennobled.

In the end of 1631 Bürgi traveled back to Kassel where he died in January 1632. His funeral took place there on January 31, 1632.

Tycho Brahe

Even higher was the worldly position into which Tyge, latinized as Tycho, Brahe was born at Knutstrup Castle in Schonen on December 14, 1546. His noble family was highly influential in Denmark to which Schonen belonged at that time, and he took up university studies which should prepare him for a high political function. But, on August 21, 1560 he observed a partial Solar eclipse, which lead him to devote his life to astronomy. On November 11, 1572, he was the first one to identify definitely a Nova in Europe.

As consequence of the letter of recommendation by Wilhelm IV King Frederick II gave Brahe both the island of Hven and financial means to build the observatories Uraniborg and Stjerneborg there. Because of the size of the instruments and their precision the measurements were about a factor 5 to 10 more exact than those of their predecessors and came to an accuracy of about 1 angular minute. Since they were mostly made of wood, however, the humidity from the sea caused problems. And: Brahe had no telescopes.

The death of Frederick II in 1588 brought a shortening of the financial means. As a consequence, Brahe left Hven together with the logs of his observations and finally followed the offer of Rudolf II to come to Prague in June 1599. As already mentioned, in 1600 Kepler became his assistant, but Brahe died on October 24, 1601.

Brahe had developed his own model of the planetary system, a hybrid of the geocentric and the heliocentric one: Only Sun and Moon circled around Earth while the remaining planets moved on circular orbits around Sun. This system gave rise to the hope that it could work without the epicycles that the other two systems had to use: In order to bring measured and calculated positions of the celestial bodies into agreement, simple circular paths around Earth had been substituted by paths where a second circular path, the "epicycle", on which the planet ran, was centered on the edge of the first circle.

It was clear for Brahe that there were no authorities from Antiquity to support his system. Therefore, he wanted to prove its validity by empirical evidence from his measured data.

How Brahe's data became Kepler's laws

Therefore, when Kepler came to Prague, Brahe assigned him the task to calculate the orbit of a planet. By lucky chance – because of its rather large eccentricity –, Mars was waiting to be done. Kepler took up this task under the assumption of circular paths of Earth and Mars around Sun, which are uniformly run through, but with the center not necessarily in the Sun. Furthermore, Kepler wished that there should be no epicycles.

Kepler thought at first that this task would take only a few days. It lasted, however, five years to find the best approximation – and then he had to realize that there still was a difference of eight angular minutes between measured and calculated positions: "Who would think that this could happen?" he asks in the beginning of Caput XIX of his *Astronomia Nova*. He did not give up, however, but took seriously Brahe's idea of proof by data. Furthermore, he did still not want to use epicycles.

So, he had to allow another curve for the orbits: Ellipses had been known since Antiquity. But Plato (428/427–348/347 B.C.) had stated that the objects that the creator of the world had made could only move uniformly on a circular path. Therefore, each astronomer before Kepler had shrunk back from other kinds of motions. (Because of his missing classical education, Bürgi, however, was not afraid of using elliptic

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[2] Cf. Andreas Schrimpf, Frank Verbunt: arXiv:2103.03034 and arXiv:2103.10801

gears in his astronomical clocks and globes.)

But Kepler felt more or less forced to use ellipses, as explicitly stated in his first law of planetary motion and implicitly in his second law. He expressed the first ideas of this “area law” already in a letter to David Fabricius (1564–1617) of July 4, 1603 and it helped him in the following to test his first law.

Kepler’s third law was only stated in his *Harmonices Mundi* of 1619 – just in the same chapter as his argument that there could only be six planets because five Platonic solids have to be put between them.

On the relation between Kepler and Bürgi

Kepler’s remark on Bürgi from the foreword of *Tabulae Rudolphinae* that the latter did not rear up his logarithms, but forsook them, is sometimes interpreted in the way that Bürgi was an arithmetic servant to Kepler who did not fulfil his duties. Recent findings and publications, however, have swung the pendulum to the opposite and sometimes lead to the impression that Bürgi had all what was necessary for Kepler’s laws besides a command of Latin.

Taking into account the new view of simulation as a third way besides experiment and theory, one might paint the situation in a more differentiated way:

Kepler was the natural philosopher, who wanted to ***understand*** the celestial system. Bürgi was the engineer, who wanted to design machines that ***reproduce*** and ***predict*** its behavior.

References

Kepler’s collected works are available at *https://kepler.badw.de/das-projekt.html*.

Kepler: From the planets to dark matter

PT 2/2021

Arnold Hanslmeier, Institut für Physik, Universität Graz, Austria

1 Historical remarks

Johannes Kepler (1571-1630) described the motion of the solar system planets by his famous three laws. From 1594-1600 he was in Graz and worked as a *Landschaftsmathematiker* and became famous because he published a calendar where by chance he made correct weather predictions. From March 1600 to October 1601 he worked in Prague with the famous Tycho Brahe and his task was to calculate the orbit of planet Mars. He realized that the orbit of Mars cannot be a perfect circle but rather an ellipse. Thus he established his first law. In this paper we will however mainly concentrate on his third law which was discovered in 1618 and published 1619 in *Harmonice mundi* (see Fig. 1).

The main idea of Kepler was to describe the planetary system and, as he thought, the whole universe as an harmonic system. There should be perfect harmony and he expressed the orbits of the planets by Platonic solids in his *Mysterium Cosmographicum* that appeared 1596 in Graz. Kepler proposed that the distance relationships between the six planets known at that time could be understood in terms of the five Platonic solids, enclosed within a sphere that represented the orbit of Saturn (Fig. 1).

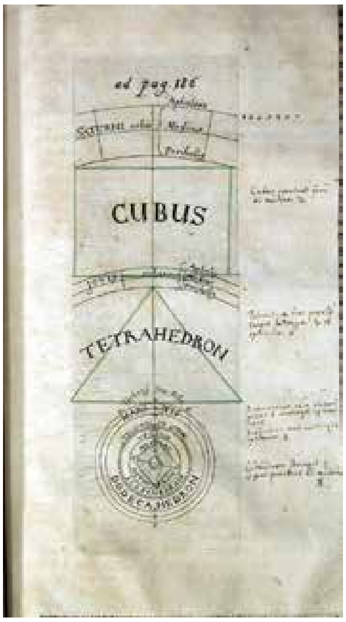

Fig. 1: Kepler used the Platonic solids to determine the position of the planets in his "Harmonice mundi".

2 Kepler’s third law

2.1 A simple derivation

Here we give a very simple derivation for Kepler’s third law by just considering circular orbits. We assume that the centrifugal force acting on a planet because of its circular motion around the Sun is balanced by the gravitational attraction. m_s is the mass of the Sun, m_P the mass of the planet, r the distance of the planet from the Sun and ω the angular velocity:

$$m_P r\omega^2 = G\frac{m_s m_P}{r^2} \qquad (1)$$

$\omega = 2\pi/T$, T the orbital period. We obtain for orbit radius $r = a$ Kepler's third law:

$$\frac{a^3}{T^2} = \frac{1}{4\pi^2}\cdot G\cdot m_\odot = 3.38\times10^{18}\ \mathrm{m^3/s^2}$$

using the gravitational constant $G = 6.67 \times 10^{-11}$ $\mathrm{m^3/(kg{\cdot}s^2)}$. Expressing a in AU (1 AU = 150 Mio km) and T in years yields

$$\frac{a^3}{T^2} = const \qquad (2)$$

This holds for any planetary system. However, since the value of the constant depends on the mass of the central star, it is different for every system. In Table 1 we give as example the values for the constant for some objects in the solar system and in the recently discovered Trappist system, which is an exoplanet system about 40 light years away from us.

Planet	a [AU]	T	const
Mercury	0.395	0.241 y	1.002
Venus	0.723	0.615 y	1.001
Earth	1.000	1.000 y	1.000
Mars	1.574	1.881 y	1.000
Neptune	30.07	161.7 y	0.996
Trappist 1b	0.0115	1.51 d	0.0888
Trappist 1e	0.0293	6.10 d	0.0900
Trappist 1 g	0.0469	12.36 d	0.0899
Trappist 1 h	0.0619	18.76 d	0.0897

Table 1: Comparison of the constant in Kepler’s third law for planets in the solar system and in the Trappist system. The values of T are given in years for solar system planets and in earth days for the Trappist planets.

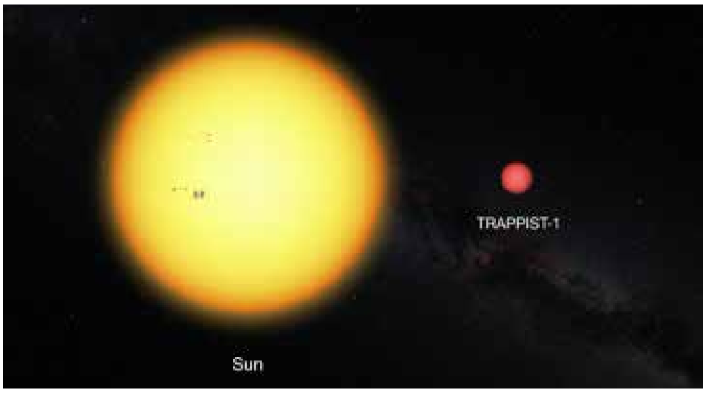

Figure 2: Comparison of the Sun and the star Trappist 1. Source: ESO.

The host star has only about 0.089 solar masses. A comparison between the size of the Sun and Trappist 1 is shown in Fig. 2.

The larger differences for the Trappist system result from uncertainties of the measured parameters. They could also be explained due to the stronger gravitational interactions between the relatively close planets.

2.2 Kepler's third law to determine distances

One straightforward application of Kepler's third law is its application to determine distances. Consider two planets 1, 2 then:

$$\frac{a_1^3}{T_1^2} = \frac{a_2^3}{T_2^2} \qquad (3)$$

If the orbit radius in the major axis (which is approximately the distance to the host star (Sun) for small eccentricity of the orbit) of planet 1 is known as well as its orbital period T_1 and the orbital period T_2 of planet 2, we obtain a_2. Thus if one distance of a planet to its host star in a planetary system is known, all other distances follow immediately.

2.3 The exact formulation fo Kepler's third law

Consider two masses M_1, M_2, where the semi major axis of the elliptic orbit of mass M_2 is a and its orbital period T, then in the center of gravity system:

$$\frac{a^3}{T^2} = \frac{G}{4\pi^2}(M_1 + M_2) \qquad (4)$$

Let us use this formula to determine the mass of the Sun. The semi major axis of Earth's orbit is $a = 1$ AU, the orbital period is 1 year ~ 3×10^7 s. Then by neglecting $M_2 << M_1$ we obtain the mass of the Sun: $M_\odot = 2 \times 10^{30}$ kg.

3 Masses in the universe

3.1 Stellar masses

The stellar mass is the crucial parameter that determines the lifetime of a star and its final evolution. The lifetime of a star can be directly expressed in terms of its mass by:

$$\tau \sim 10^{10}\left(\frac{M_\odot}{M}\right)^{2.5} y \qquad (5)$$

Thus for the Sun the lifetime is about 10^{10} y, for a star with 5 solar masses it is only 180 million years.

Masses can be determined only in the case a star has a companion and the distance of the companion (could be another star or a planet) to the star as well as its orbital period are known. Then we can directly use the exact formulation of Kepler's third law.

Stellar masses determine the ultimate evolution of a star. Stars lose an important fraction of their mass in their lifetime due to stellar winds, or in the final phases, depending on their mass, in explosions like the ones we see in supernovae. This leads to the following:

- Stellar remnants with masses $M < 1.44\,M_\odot$ finally evolve into earth-sized compact white dwarfs. 1.44 solar masses is the Chandrasekhar limit. Below this mass the degenerate electrons can provide the pressure against gravity in the final stellar evolution.
- Stellar remnants with masses $1.44\,M_\odot < M_* < 2...3\,M_\odot$ end up as neutron stars (where the pressure of the degenerate neutrons resists gravity).
- Stellar remnants with masses $> 2...3\,M_\odot$ end up as black holes where the star completely collapses.

3.2 The mass of the Galaxy

The solar system is just one out of several 100 billion stars in the Milky Way, also called the Galaxy. The mass of the Galaxy can be obtained by stellar statistics, e.g. counting stars in selected fields. A more accurate determination of the mass of the Galaxy results again from Kepler's third law. Our galaxy is a spiral galaxy and the Sun is located at a distance of about 8.5 kpc (about 30.000 light years) from the center of the Galaxy. It orbits around the galactic center in about 220 million years. Using Kepler's third law with the values: $a = 8.5$ kpc $= 8.5 \times 10^3 \times 3.26 \times 10^{16}$ m $= 2.77 \times 10^{21}$ m and $T = 220 \times 10^6 \times 3 \times 10^7$ s $= 6.6 \times 10^{15}$ s leads to a mass of $1.765 \times 10^{11}\,M_\odot$. Of course this is only an estimate since we neglected all the mass of the Galaxy outside the orbit of the Sun.

Galaxies always occur in clusters and by the dynamics of the cluster members we again can estimate masses.

3.3 Supermassive black holes

The center of our galaxy cannot be observed in the visible part of the electromagnetic spectrum because of interstellar absorption. Observations with high resolution telescopes

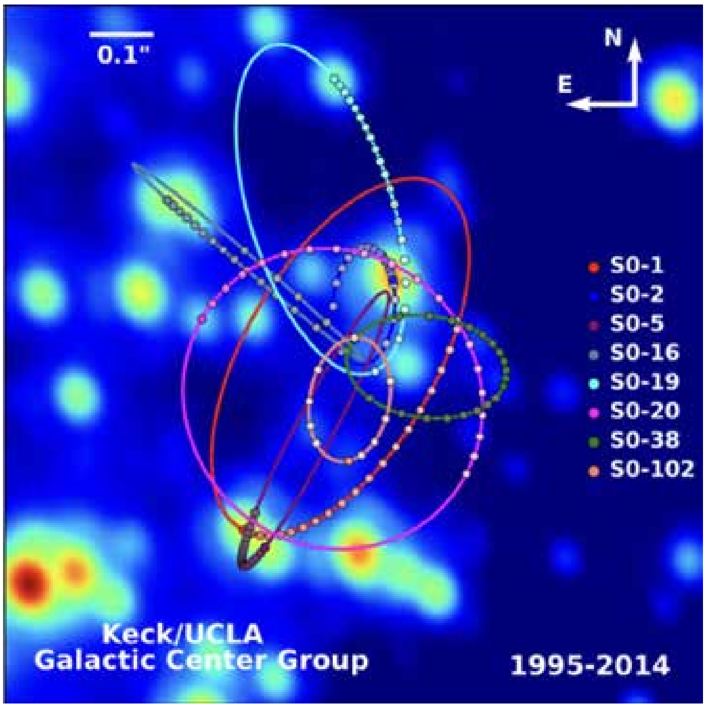

Figure 3: Observations from the Keck telescope; the positions of stars near the galactic center are shown and they indicate a rotation about a central massive object. Source: Keck/UCLA.

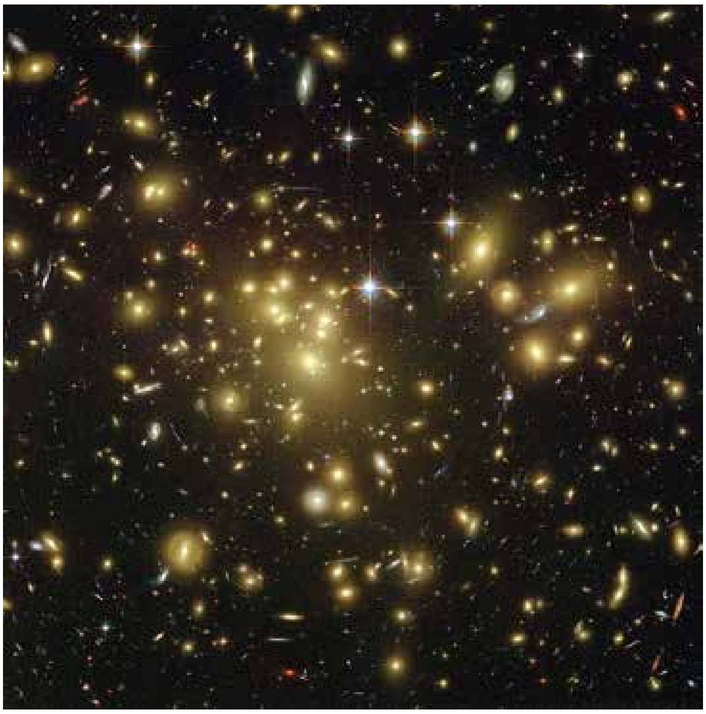

Figure 4: A galaxy cluster (Abell 1689) that produces gravitational lensing of galaxies behind it. Source: Hubble Space Telescope.

(like the two 10-m Keck telescopes that can be operated as an interferometer in the IR) show individual stars only several 1000 AU away from the center. Time series of observations covering about 20 years show the motion of such stars about the center (see Fig. 3). Using Kepler's third law we can calculate the central mass around which these stars orbit: for example if $a = 3000$ AU and $T = 40$ years, then the central mass would be 18.6 million solar masses. From the fact that no radiation is received from the central star, it can be concluded that it could be a supermassive black hole. The formation of supermassive black holes, which are observed also in other galaxies' centers, must have occurred during the early evolution of the universe.

4 Dark matter

4.1 First hints for dark matter

Galaxies occur in clusters, for example our Galaxy belongs to the so called local group (a prominent member is our neighboring galaxy, the Andromeda Galaxy). In the 1930s the Swiss astronomer Fritz Zwicky examined galaxy clusters. He realized that these clusters cannot be in dynamical equilibrium, since they are unstable and should dissolve over several hundred million years. Since galaxy clusters are observed also at extremely large distances of several billion light years they must be stable and Zwicky introduced the missing mass concept to explain their stability. This additional mass can, for some reason, not be observed.

4.2 Dark matter in galaxies

When we investigate the rotation curve of a galaxy we would expect the following behavior: the farther an object (e.g. a star) is from the center of its host galaxy, the larger should be its period of revolution because

$$\frac{a^3}{T^2} = const \qquad (6)$$

However, it was found that at larger distances from the galactic center, the speed remains constant or in several cases even increases. This can be only explained by the presence of additional matter that does not radiate, called *Dark Matter*. It can be shown that the amount of dark matter is about five times higher than ordinary visible matter. The presence of dark matter around galaxy clusters can also be inferred from gravitational lensing effects. If, seen from us, there is a galaxy behind a galaxy cluster, then because of the presence of a large mass in the galaxy cluster, light from the more distant galaxy will be bended because of space-time curvature according to general relativity theory. It also became clear that the observable matter of a galaxy cluster is not sufficient to explain the lensing effects.

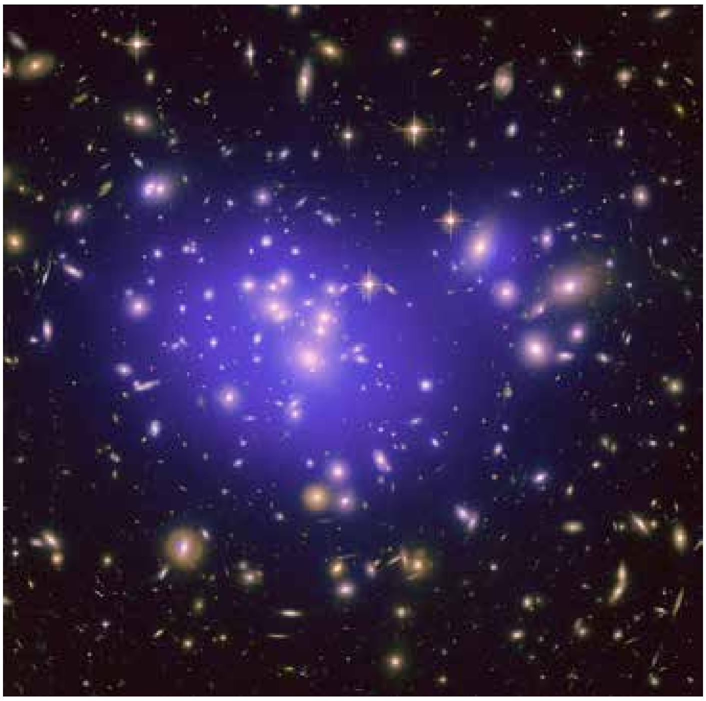

Figure 5: Galaxy cluster (Abell 1689) that produces gravitational lensing of galaxies behind it. Here the distribution of dark matter is indicated by blue color. Source: Hubble Space Telescope.

In Fig. 4 the galaxy cluster Abell 1689 is shown. This cluster is at a distance of about 2.2 billion light years. One clearly sees some lensing effects (curved images of fainter galaxies). The deflection of a light beam is deduced from general relativity (the value here is twice the value from Newtonian physics where light is assumed to consist of massive particles):

$$\theta = \frac{4GM}{rc^2} \qquad (7)$$

where M is the mass (in our case the mass of the galaxy cluster), r the distance of the passing light beam from the mass. In Fig. 5 we show the calculated distribution of dark matter (in blue) around the galaxy cluster. This was obtained by modeling the gravitational lensing.

5 Conclusion

We have shown that Kepler's law can be applied to various astrophysical topics, planets, stellar masses, galaxies and these equations finally even lead us to the concept of dark matter. We give also some simple numerical examples of these applications.

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The first image of a black hole

PT 3/2021

Luciano Rezzolla [1,2,3] and The Event Horizon Telescope Collaboration
[1] Institut für Theoretische Physik, Max-von-Laue-Straße 1, 60438 Frankfurt am Main, Germany
[2] Frankfurt Institute for Advanced Studies, Ruth-Moufang-Str. 1, 60438 Frankfurt am Main, Germany
[3] School of Mathematics, Trinity College, Dublin 2, Ireland

When surrounded by a transparent emission region, black holes are expected to reveal a dark shadow caused by gravitational light bending and photon capture at the event horizon. To image and study this phenomenon, in April 2019, the Event Horizon Telescope (EHT) Collaboration reported the first observations of a global very long baseline interferometry (VLBI) array observing at a wavelength of 1.3 mm. These observations have allowed us to reconstruct event-horizon-scale images of the supermassive black hole candidate in the center of the giant elliptical galaxy M87.

We have resolved the central compact radio source as an asymmetric bright emission ring with a diameter of $42 \pm 3\,\mu$as, which is circular and encompasses a central depression in brightness with a flux ratio $\gtrsim 10:1$ (see Fig. 1). The emission ring is recovered using different calibration and imaging schemes, with its diameter and width remaining stable over four different observations carried out in different days. Overall, the observed image is consistent with expectations for the shadow of a Kerr black hole as predicted by general relativity. The asymmetry in brightness in the ring can be explained in terms of relativistic beaming of the emission from a plasma rotating close to the speed of light around a black hole. By comparing the EHT observed images to an extensive library of ray-traced general-relativistic magnetohydrodynamic (GRMHD) simulations of black holes, it was possible to derive a central mass of $M = (6.5 \pm 0.7) \times 10^9\,M_\odot$.

While the capability of the Event Horizon Telescope (EHT) to image the nearest supermassive black hole candidates at horizon-scale resolutions offers a novel means to study gravity in its strongest regimes and to test different models for these objects, it is not always simple to rule out alternatives to black holes in general relativity. Indeed, while the Kerr metric remains a solution in some alternative theories of gravity, non-Kerr black hole solutions do exist in a variety of such modified theories. This is because a shadow can be produced by any compact object with a spacetime characterized by unstable circular photon orbits [2]. Furthermore, exotic alternatives to black holes, such as naked singularities [3] and gravastars [4, 5], are admissible solutions within general relativity and provide concrete, albeit contrived, models. Some of such exotic compact objects can already be shown to be incompatible with our observations given our maximum mass prior. For example, the shadows of naked singularities associated with Kerr spacetimes with $|a_*| > 1$ are substantially smaller and very asymmetric compared to those of Kerr black holes [6].

In order to assess our present ability to use EHT images to determine if they correspond to a Kerr black hole as predicted by Einstein's theory of general relativity or to a black hole in alternative theories of gravity. To this end, we have performed (GRMHD) simulations and use general-relativistic radiative transfer (GRRT) calculations to generate synthetic shadow images of a magnetised accretion flow onto a Kerr black hole. In addition, and for the first time, we have performed GRMHD simulations and GRRT calculations for a dilaton black hole, which we take as a representative solution of an alternative theory of gravity. Adopting the VLBI configuration from the 2017 EHTC campaign, we find that it could be extremely difficult to distinguish between black holes from different theories of gravity [2] (see Fig. 2). These results highlight that great caution is needed when interpreting black hole images as tests of general relativity.

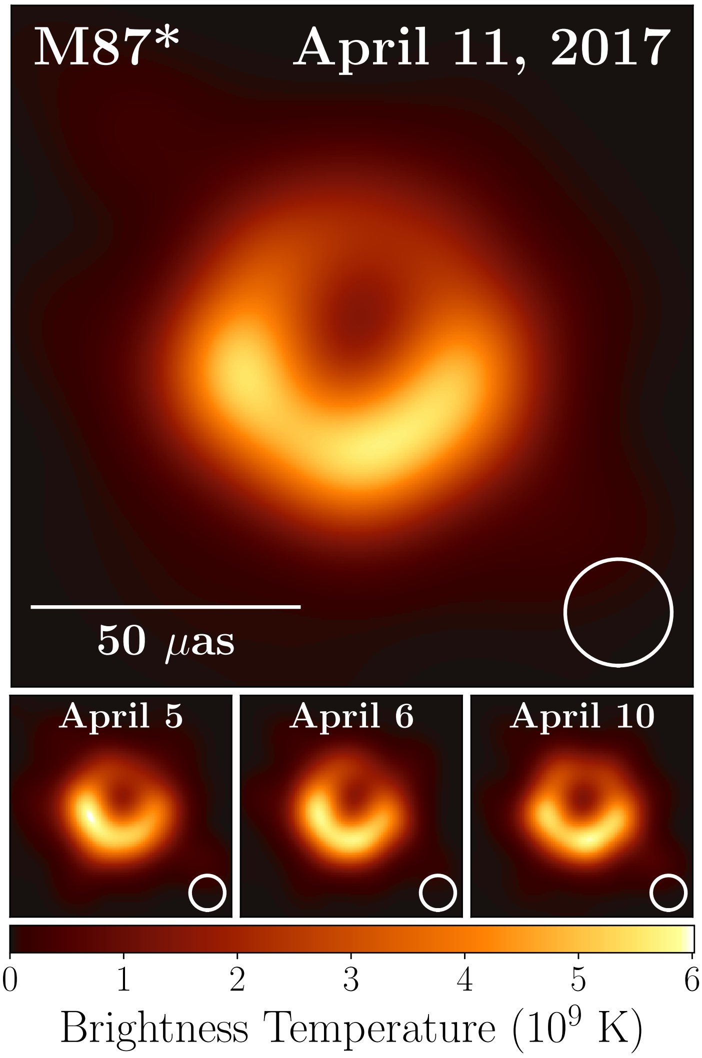

FIG. 1. Top: EHT image of M87 from observations on April 11, 2017 as a representative example of the images collected in the 2017 campaign. The image is the average of three different imaging methods after convolving each with a circular Gaussian kernel to give matched resolutions. The largest of the three kernels (20 µas FWHM) is shown in the lower right. The image is shown in units of brightness temperature, $T_b = S\lambda^2/2k_B\Omega$, where S is the flux density, λ is the observing wavelength, k_B is the Boltzmann constant, and Ω is the solid angle of the resolution element. Bottom: Similar images taken over different days showing the stability of the basic image structure and the equivalence among different days.*

Finally, when interpreting the EHT images it can be instructive to other compact-object candidates – such as boson stars – which possess an unstable circular photon orbit but

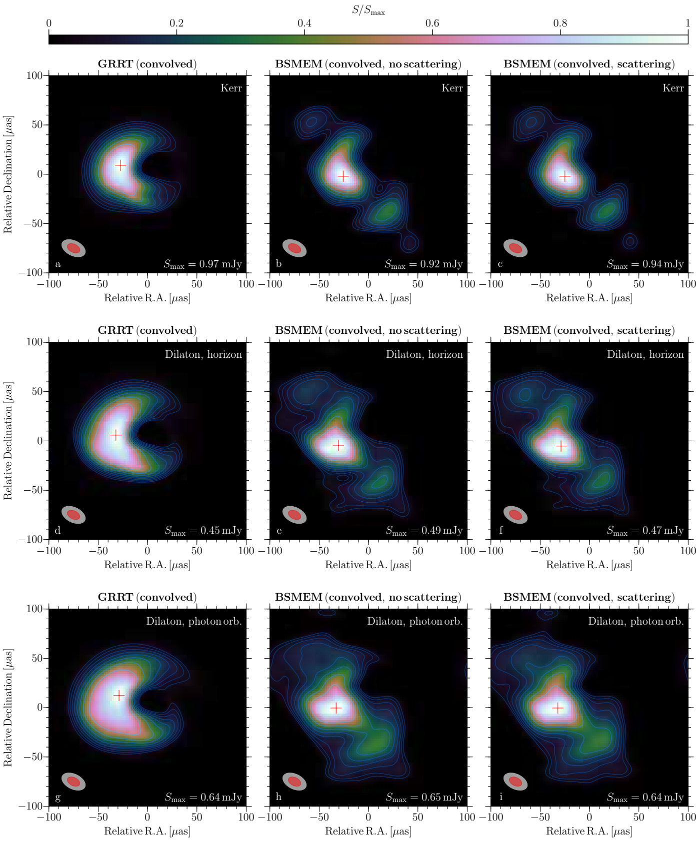

FIG. 2. Synthetic BH shadow images of Sgr A for the Kerr BH using two different image reconstruction algorithms. From left to right: GRRT image convolved with 50% (red shading) of the nominal beam size (light grey shading), the contour levels start at 5% of the peak value and increase by $\sqrt{2}$. The red cross in the images marks the position of the flux density maximum (panel a), reconstructed image without interstellar scattering convolved with 50% (red shading) of the nominal beam size (light grey shading, panel b), and reconstructed image without interstellar scattering using BSMEM (panel c). All images are based on visibilities which take into account a possible VLBI antenna configuration and schedule for the EHTC April 2017 observations. The convolving beam is plotted in the lower left corner of each panel (see Ref. [2] for details).*

are without a surface or an event horizon [7, 8]. In such spacetimes, null geodesics are redirected outwards towards distant observers [9], so that the shadow can in principle be filled with emission from lensed images of distant radio sources generating a complex mirror image of the sky.

Also in this case, we have performed GRMHD simulations of accretion flows in the boson-star spacetime, followed by GRRT calculations. The synthetic reconstructed images considering realistic astronomical observing conditions show that, despite qualitative similarities, the differences in the appearance of a black hole – either rotating or not – and a boson star are large enough to be detectable [10] (see Fig. 3). The origin of this difference is to be found in the fact that accretion flows onto boson stars behave differently from the corresponding flows onto black holes. These differences arise from dynamical effects directly related to the absence of an event horizon, in particular, the accumulation of matter in the form of a small torus or a spheroidal cloud in the interior of the boson star, and the absence of an evacuated high-magnetisation funnel in the polar regions. The mechanism behind these effects is general enough to apply to other horizonless and surfaceless black hole mimickers, strengthening confidence in the ability of the EHT to identify such objects via radio observations.

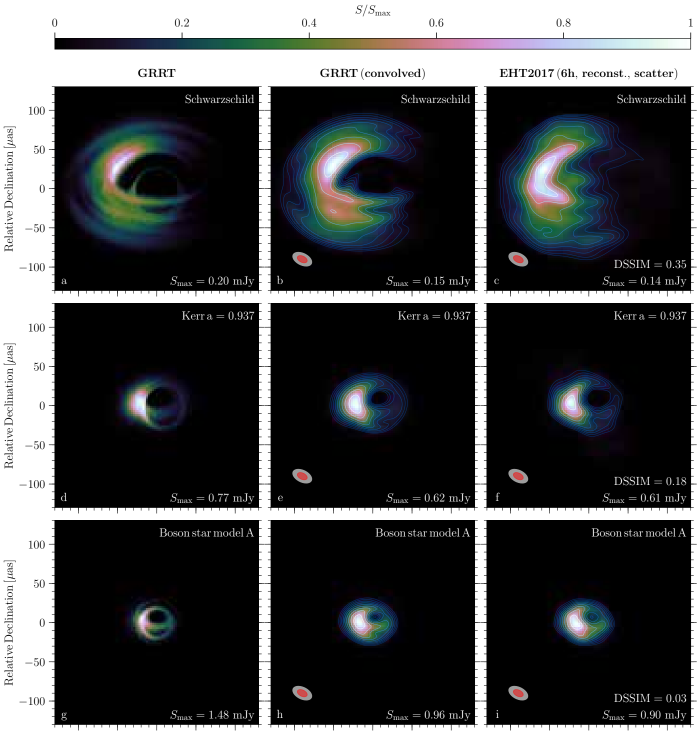

FIG. 3. From top to bottom: ray-traced and synthetic images at 230 GHz and inclination angle of θ_{obs} = 60° of the Schwarzschild black hole (first row), the Kerr black hole (second row), and boson-star models A (third row). From left to right, first column: ray-traced images averaged over the interval $t/M \in [8900, 10000]$, second column: ray-traced images convolved with 50% (red shaded ellipse) of the EHTC beam (grey shaded ellipse), third column: reconstructed images including interstellar scattering, convolved with 50% (red shaded ellipse) of the EHTC beam (grey shaded ellipse) and indicating the value of the DSSIM metric (see Ref. [10] for details).

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PT 4/2021

Where Physics Meets Chemistry: Surfaces at the Atomic Scale

Ulrike Diebold, Institute of Applied Physics, TU Wien, Wiedner Hauptstrasse 8-10/134, AT-1050 Wien
ulrike.diebold@tuwien.ac.at

The arrangement of the top layer of atoms on a solid and the resulting electronic and chemical surface properties affect and sometimes even dominate a material's functionality. Surface science seeks to understand such properties at the most fundamental, the atomic level. In the past decades, many experimental techniques have been developed to study solid surfaces with exquisite detail. The combination with theoretical modeling, mainly based on density functional theory (DFT), allows mechanistic insights into surface chemical reactions.

Efficient DFT codes are available for modeling unit cells with several hundred atoms [1]. These 2D slabs have well-defined atomic coordinates and include a layer of vacuum. They interface ideally with surface science experiments where samples are usually single crystals with well-defined structures and compositions. Investigations are typically conducted in ultrahigh vacuum (UHV), i.e., at a pressure range of less than 10^{-10} mbar. Atomically-resolved images of surfaces and adsorbed molecules are obtained with Scanning Tunneling Microscopes (STM) and the latest non-contact Atomic Force Microscopes (ncAFM) [2].

The combination of theory and experiments is mutually beneficial. On the one hand, computational insights are essential for interpreting experimental results. On the other hand, atomically resolved data can provide stringent benchmarks for the approximations used in DFT. One prime example is the degree of localization of excess charge carriers in ionic solids [3]. These so-called polarons are not well described with common DFT schemes, and directly observing them in atomically-resolved images has helped choose suitable approximations [4].

My talk briefly discussed two examples of this powerful combination. The first example entails a novel method to assess a fundamental chemical quantity, the proton affinity (PA). It describes the propensity of a chemical entity to gain or release a proton and is an essential parameter in de/hydrogenation reactions. The PA is well established for molecules. However, solid surfaces are heterogeneous, and the PA for any given surface atom will vary depending on its immediate surroundings. Figure 1a shows a single-crystalline In_2O_3(111) surface, where four different types of surface O atoms are present. By measuring force-distance curves with an appropriately-prepared ncAFM tip and modeling these with DFT (Fig. 1b), a PA could be assigned to each of the surface oxygen atoms [5]. We also used the same tip to probe the PA of other samples. The method can be applied generally, and an evaluation of the acidity of surface atoms next to steps, defects, impurities, or molecules should be possible [6].

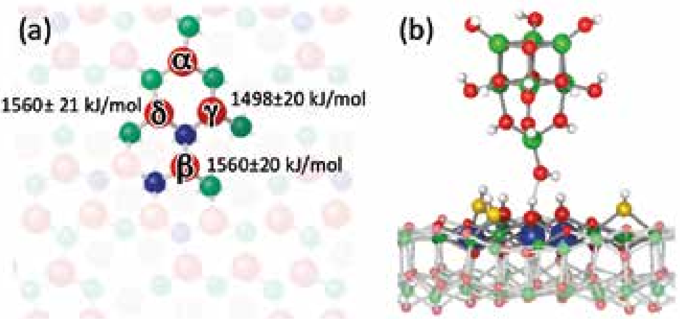

Figure 1. Measuring fundamental surface properties, one atom at a time. (a) Top view of an In_2O_3(111) surface with four different types of surface oxygen atoms (red, labelled $\alpha - \delta$). Each one is bonded to three indium atoms (blue, green) with characteristic bond lengths and angles, which results in the different proton affinities indicated. (b) The tip of a non-contact atomic force microscope in front of a hydroxylated In_2O_3(111) surface, taken from a DFT calculation modeling force-distance curves that were used to determine the values given in (a). For details see reference [5]

Surface science can deliver critical insights in the emerging field of 'single-atom catalysis (SAC)' [7]. Heterogeneous catalysts contain small particles of (often noble) metals, supported on an inexpensive material, usually an oxide. In SAC, these metal clusters are shrunk to their smallest dimensions; one metal atom is bound in a specific way to its support material. The potential advantages are obvious. Less expensive metal is needed, and high selectivity towards specific reaction products could be achieved if all sites were uniform. It is not straightforward, however, to ascertain active sites in technical catalysts. It is also not clear if established paradigms that guide the choice of the active metal will hold when its size is reduced to one single atom. Ref. [8] reports a systematic study where many experimental surface science experimental techniques were applied to the same model support. At the Fe_3O_4(001) surface, catalytically-relevant transition metals all adsorb at equivalent sites (Fig. 2). The adsorption energy of CO, traditionally used to gauge surface reactivity, was measured and computed. The excellent agreement between theory and experiment allowed us to evaluate the results in terms of established concepts.

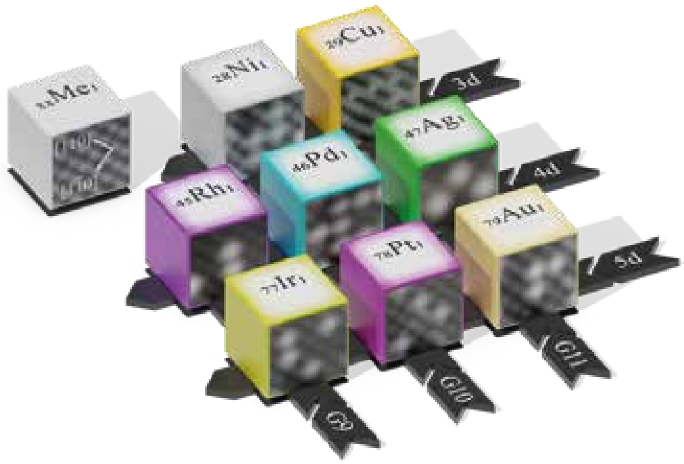

Figure 2. Model 'single-atom' catalysts. The schematic shows metals that were vapor-deposited at room temperature on a single-crystalline Fe_3O_4(001) surface and investigated in ref. [8]. As indicated by the small-scale STM images, each metal forms isolated atoms, adsorbed at the same specific site. The adsorption energy of CO was systematically investigated.

Emerging trends in surface science strive to extend measurements towards less idealized environments, such as higher gas pressures [9] or aqueous environments [10]. At the same time, computational methods are developed to accelerate theoretical calculations significantly. Such developments will lead to essential contributions in the urgent need to find more efficient energy conversion schemes.

Acknowledgment. We are grateful to the funding agencies that have supported our work throughout the years, particularly the Austrian Science Fund FWF (Projects Wittgenstein-preis Z250-N7 and SFB TACO F81) and the European Research Council ERC (Project #88395 'WatFun'). I am also indebted to Gareth S. Parkinson and Margareta Wagner for allowing me to feature their work, and to Matthias Meier for permission to use his artwork in Fig. 2.

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Physics & Education – Perspectives from Particle Physics

PT 5/2021

Hans Peter Beck, IPPOG Chair 2013-2019

Tackling deep questions on the structure, inner working, birth, evolution and fate of the Universe are challenging endeavours, often requiring scientific collaborative effort in designing and realizing projects of unprecedented scales and complexity – in all aspects and metrics considered.

Particle physics research has a long tradition of making important scientific advancement through large-scale collaborative efforts. Many of these projects started at the national level, but quickly grew to become international in scope and, by pure necessity to master the complexity that arises when large-scale projects are realised successfully, have evolved into fully global enterprises.

Through these efforts, not only science paces ahead but society as a whole has the chance for advances for the better in many aspects of scientific, philosophical, societal and economical values, when world-views evolve, when large collaborations learn to work together without borders, and when spin-offs occur that become applications of wide use [1].

However, despite a long list of successes made and new promising projects being sought, fostering consent for new large-scale infrastructure to be considered is all but easy, nor straight forward. Not only a scientific consent is needed, but societal support is needed as well. In today's so-called "post-factual world" emerging from political ideology, ignorance or complete mistrust in democratic institutions, it becomes even more apparent how high the challenges that need to be faced really are.

This problematic has been understood already more than 70 years ago, as the following quote states it with much foresight: "*It is crucially important that the general public has the opportunity to inform itself knowledgeably and intelligibly on the endeavours and results of scientific research. Restricting scientific findings to a small group of people weakens the philosophical spirit of a nation and leads to its intellectual impoverishment.*" [Albert Einstein, Princeton 1948]

However, 70 years after Einstein's quote, it has become evident that the duty is not on the side of the general public to proactively inform itself. In contrary, the duty is on the side of physicists to make sure that not only opportunities to inform oneself knowledgeably and intelligibly are made available, but that a real engaging dialogue with a broad audience is established.

It has also become evident that the tools and methods currently used to support such a dialog have not been as successful as one would have hoped for. Indeed, many activities at research centres, at universities, and museums often attract only those people who are already interested and appreciative of the basic and fundamental relevance of science.

New paths in reaching out must though be explored, without compromising the established ways, which remain truly relevant for all those who are interested in science. These must always be given the opportunity to engage further and deeper.

It is those who are not immediately interested or do not show a self-driven interest in engaging further that make out large portions of society. Finding ways to reach out further is therefore a crucial act for society, and with it also for continued and broad support of science, especially of the often called ‘blue sky research’ without seemingly imminent economic value.

Involving and engaging young and very young pupils and students comes with a special benefit. Indeed, fostering programs targeting high-school students and their teachers in the methods and tools used in fundamental science is a well deserving investment in the future. Not only will few of these young students become one day scientists themselves, but all of these young students will find their role in society. All of them can be ambassadors of the scientific method and of science-based decision taking, whenever it is about discussing the scientific approach to acquire knowledge and to base decisions upon careful reflections of information over beliefs and ideology.

Paving ways to reach out further to those who no-longer are students but who are now active in their life, is of enormous relevance and involves taking courageous steps. Partnering with artists, musicians, and celebrities, science can get into the spot light. Not ending up in trivialities but raising curiosity and interest is a tightrope walk but one with enormous potential that already has demonstrated to build interest, while keeping the spot light on science.

IPPOG – The International Particle Physics Outreach Group

With the unprecedented global scale of the Large Hadron Collider (LHC) came a real and explicit need for extensive efforts in communication, education, and outreach. This in turn has led to the creation of new communication and outreach networks more than 20 years ago. The European Particle Physics Outreach Group (EPPOG) was formed in 1997 under the joint auspices of the European Committee for Future Accelerators (ECFA) and the High Energy Particle Physics Board of the European Physical Society (EPS-HEPP). EPPOG widened its regional scope to become an international player in 2005 with the development of the International Particle Physics Masterclass programme, which is also reflected by its new name, now to be called the International Particle Physics Outreach Group (IPPOG) in 2011 [2]. With the growing global scale and scope of its activities, IPPOG became an international collaboration in 2016, following the way large-scale international scientific collaborations are built and function [3]. This has enabled IPPOG to secure limited financial support at a critical time, allowing it to continue to extend its network and develop much-needed infrastructure.

IPPOG is a network of scientists, science educators and communication specialists working across the globe in informal science education and outreach for particle physics. The declared goal is to bring new discoveries in this exciting field to young people and to convey to the public that the beauty of nature is indeed understandable from the interactions of its most fundamental parts - the elementary particles. Today, the IPPOG collaboration comprises 37 members (30 countries, 6 experiments and CERN as an international laboratory) and 2 associate national laboratories as associated members.

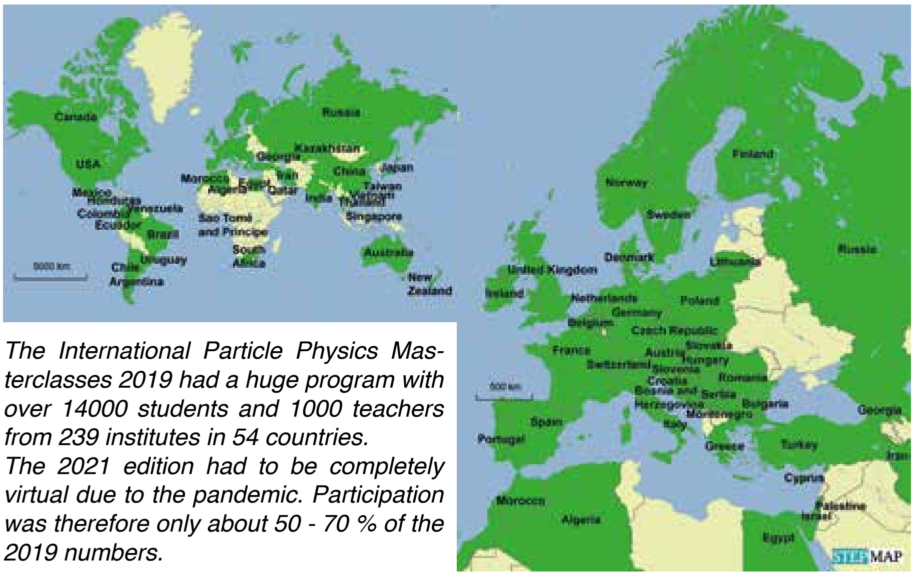
The 17th IPPOG Collaboration meeting 2019 in Darmstadt.

The primary methodology adopted by IPPOG requires the direct involvement of scientists active in current research with education and communication specialists, in order to effectively develop and share best practices in outreach. IPPOG member activities include the International Particle Physics Masterclass programme, the International Day of Women and Girls in Science, the Worldwide Data Day, the International Muon Week and the International Cosmic Day organisation [4], and participation in a wide range of activities from public talks, mounting science pavilions at festivals, setting up new exhibitions, teacher training, student competitions, and supporting open days at local institutions. These independent activities, often carried out in a variety of languages to a broad public with a variety of backgrounds, all serve to gain the public trust and to improve worldwide understanding and support of science.

IPPOG Masterclasses

It is worth pointing out one of IPPOG’s activities, which helped gaining its world-wide reputation most, the IPPOG Masterclass [5]. A Masterclass differs from a typical class, as it is taught by an expert in the field, who is not necessarily a professional educator. The advantage of such extra-curricular or informal training is that students take a break from their usual routine and be inspired by experts and role models in their specialty. IPPOG Masterclasses are run by parti-

International Particle Physics Masterclasses are the flagships of IPPOG. Here students become "researchers for a day", getting to know the various aspects of scientific methods and workflows.



The International Particle Physics Masterclasses 2019 had a huge program with over 14000 students and 1000 teachers from 239 institutes in 54 countries.
The 2021 edition had to be completely virtual due to the pandemic. Participation was therefore only about 50 - 70 % of the 2019 numbers.

cle physicists and are targeted to high-school students, who typically team up at a local university for a full-day immersion into a topic mostly new to them. The students get exposed to work with current data analysis tools and event displays, on real data from active experiments, such as e.g. ATLAS, CMS, or LHCb, to name only those LHC experiments with Swiss participation, and they also have a chance to engage in conversation with the physicists. They learn, in essence, what it is like to be a particle physicist, if only for a day.

IPPOG Masterclasses have become an institution in many ways and at many universities and laboratories around the globe, with approaching 240 institutes from 54 countries welcoming more than 14’000 students and over 1000 of their teachers annually. Participation in 2021 was reduced to 50 - 70 % of these peak numbers and before the pandemic caused masterclasses to become mostly online events, where they are losing much of its original spirit and impact. Once the pandemic behind us, in-person masterclass events will again guarantee for full immersion and exposure of the participating students, allowing again for a full day with a lasting impact.

Reaching out further

Educating the young and the very young is relatively easy and special programs can be created and targeted towards school students and their teachers. More difficulties arise when initiating programs for the so-called active population. Only the most interested will take up the initiative to find themselves engaged in a science fair or open day event at a local university. Going where people go is therefore key and being active in public engagement, giving talks at various events, from science festivals to film screenings, open days, pubs, cafes, libraries, and more becomes paramount.

Demonstrations and exhibitions at music festivals have been realized to be effective. Especially festivals that last multiple days, where the participants often live in tents and have ample of spare time between performances of their favorite music groups, offer a chance that was not realized before. The WOMAD Festival in the UK, the Colours of Ostrava festival in the Czech Republic, the Pohoda festival [6] in Slovakia have regular annually recurring science tents with impressive numbers of audience strolling in and then finding themselves captivated by the material presented and activities to engage in.

Science as an integral part of culture of today

As the ongoing pandemic shows, science and applying it at its broadest scale to society at large comes along with broad discussions, demonstrations and frustration is triggered on both sides: those who understand the scientific method and how knowledge and understanding evolves and therefore understand how applications and tools come into existence, and those who feel overrun by new applications that sometimes are perceived as being imposed, and hence can trigger fierce reactions. Science is indeed an integral part of society and culture today – in all aspects of life. Coming back to particle physics and to any new big-scale project anticipated to be proposed [7], it will need concerted, global education, outreach, and communication efforts, with a strong and engaging dialogue with the public and stakeholders, and adequately educating pupils and students at all ages [8].

To achieve this, physicists are needed who can engage in a scientific collaborative way, together with educators, writers, coders, communicators and more. Hence the strategic importance of a collaboration like IPPOG, not only in particle physics and for its next ambitious projects, but globally for all science to convey its enormous value and relevance to society.

In addition, there is a much-wanted side effect when engaging as a physicist with the public, as has been put adequately by Viki Weisskopf already in 1972:
“*More concerted and systematic effort toward presentation and popularization of science would be helpful in many respects; it would provide a potent antidote to overspecialization; it would bring out clearly what is significant in current research, and it would make science a more integral part of the culture of today.*” [9]

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The Future Circular Collider Feasibility Study

PT 6/2021

Michael Benedikt, CERN

The Higgs boson, discovered in 2012 by the ATLAS and CMS experiments at CERN's Large Hadron Collider, is a cornerstone of the Standard Model (SM). Despite the completion of its particle contents by the Higgs boson discovery, the Standard Model does not account for a large amount of experimental evidence, such as the nature of dark matter, the origin of the matter–antimatter asymmetry in the Universe, and the existence and hierarchy of neutrino masses. Measuring the properties of the Higgs boson and studying its interaction with the other particles of the SM and with itself, poses a key experimental challenge for the 21st century.

Addressing these questions calls for a new generation of more powerful and efficient particle colliders like those envisioned by the Future Circular Collider (FCC) study. The 2020 Update of the European Strategy for Particle Physics [1], a bottom-up approach, concluded that "*Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update*". An electron-positron collider, as a possible first step in the "FCC integrated programme" (see Figure 1), followed by a 100 TeV high-energy proton collider (FCC-hh), housed in the same tunnel and profiting from the common infrastructure, complies with this guideline.

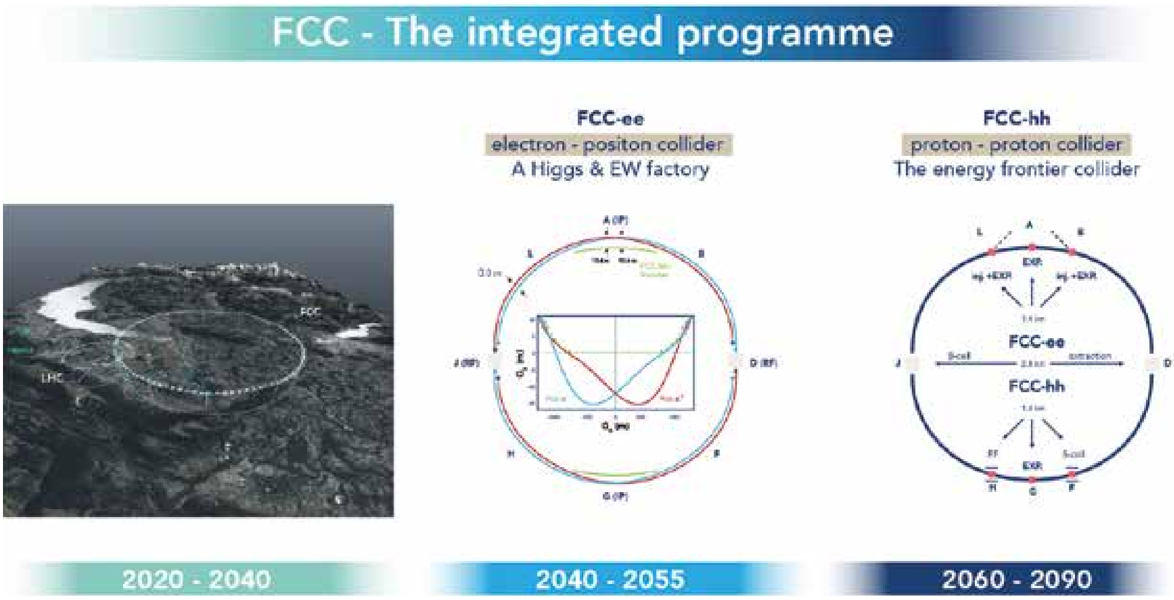

Figure 1: The FCC integrated program

Indeed, inspired by the successful history of LEP and the LHC, the FCC integrated programme offers a comprehensive long-term research programme that maximises the physics opportunities through synergies and complementarity with other projects. The initial luminosity-frontier highest-energy electron–positron collider (FCC-ee) would collide particles at centre-of-mass energies ranging from 91 GeV to 365 GeV. These energies allow studying the W and Z bosons, Higgs boson and top quarks with unprecedented precision, testing the consistency of the SM. A lepton collider would also work as a Higgs factory, producing billions of Higgs bosons and allowing the detailed investigation of their coupling and interactions along with sensitive searches for signs of new physics.

The largest part of the FCC-ee infrastructure could be reused for FCC-hh, providing proton–proton collisions at a center-of-mass energy of 100 TeV. The FCC-hh will use the "FCC-ee standard candles" to further improve the statistics accuracy while it could produce particles with much higher mass (up to 40 TeV) far beyond the energy limits of the LHC. In addition, FCC-hh offers the unique opportunity to measure the Higgs self-coupling with a precision of less than 5% and explores the dynamics of electroweak symmetry breaking and its role in the evolution of our Universe. Furthermore, thermal dark matter candidates would either be discovered or conclusively ruled out by FCC-hh. Other opportunities at the new infrastructure include heavy-ion and electron–proton collisions (FCC-eh) adding to the breadth of the overall FCC physics program.

The construction of any future collider represents a substantial investment. It should be an integral part of a long-term vision of high-energy physics, maximising the total physics output and providing a diverse physics programme, while minimising overall cost. The FCC integrated plan, extending over 70 years in time as illustrated in Fig. 2, was developed to fulfil all the aforementioned goals and serve the particle physics community through the end of the twenty-first century.

Despite its long horizon up to the end of the 21st century, the timescales for the realization of the FCCs are rather tight, calling for a global coordinated R&D effort in a number of fields beyond physics. A post-LHC collider should be operational around 2040's, ensuring a smooth continuation after the LHC/HL-LHC programme. Consequently the construction to host these new colliders should start in the early 2030's with the first physics run taking place in the 2040's, after the end of the HL/LHC's lifetime.

Towards this goal, and in line with the 2020 EPPS recommendations, the FCC feasibility study was launched in 2021. It focuses on the regional implementation scenario in

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[1] https://home.cern/news/news/physics/particle-physicists-update-strategy-future-field-europe

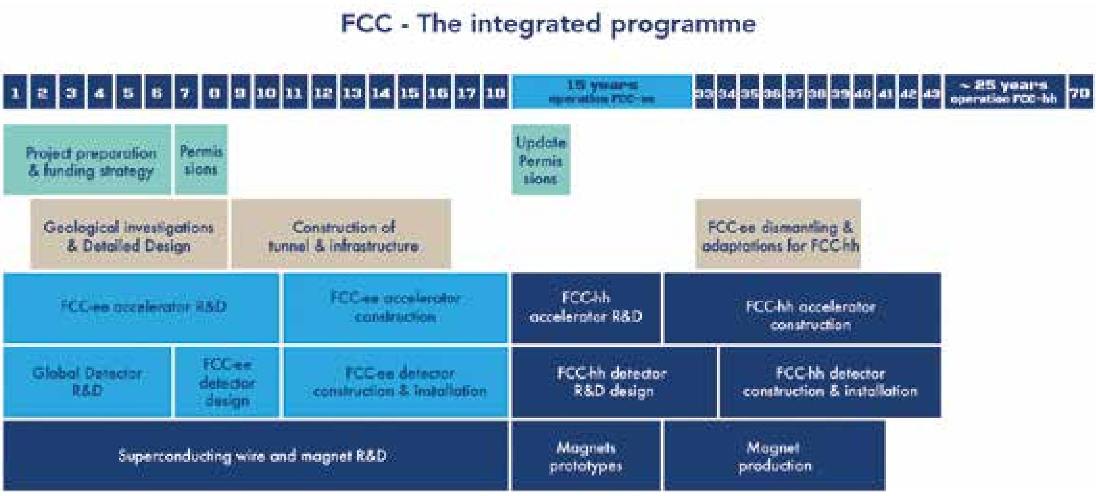


Figure 2: Overall time schedule for the FCC integrated program

accordance with CERN's Host States, the optimization of the machine parameters including the advancement of vital technologies to improve its performance and the development of a global collaboration - including the future users of this facility - with the support of the SWISS CHART and the EC H2020 FCCIS design study. In parallel, Europe has launched a high-field magnet R&D programme to pave the way for an energy-frontier collider (FCC-hh).

As mentioned, placement studies for the new tunnel and surface infrastructure and the development of concepts for the environmental evaluation are two of the key focus areas of the FCC feasibility study. The placement process is driven by an iterative multi-criteria optimization based on the principle of "Éviter-réduire-compenser" (Avoid-Reduce-Compensate). This is a delicate task, balancing geological and territorial constraints with the machine requirements and without sacrificing the top physics performance required by these machines. Preliminary results have revealed that the most suitable scenarios for the new ring are based on a 91 km circumference tunnel with 8 surface sites while other options are still being considered. Vital in the layout design are the ongoing geodetic measurements in the region, offering data that will allow the high-precision alignment of the accelerator's components. Further advancement would also require subsurface investigations of high-risk areas, surface site initial state analysis and public consultation with the local population. On the civil-engineering front, a 3D geological model for the Geneva basin has been developed along with Swiss and Austrian academic and industrial partners. Finally, the feasibility study should cover the development of a management plan for the ~9 million cubic metres of excavated materials, mainly Molasse, expected from the civil engineering work. To identify novel solutions and engage new partners, the international competition "Mining the Future" was launched in May 2021 to solicit input for technically, commercially and societally valid reuse approaches.

Building and operating a new infrastructure in a sustainable way poses a number of technological challenges for machine design. Particle beams in circular accelerators experience energy loss from synchrotron radiation, but this is reduced for larger circumferences. The lower loss in the 100-km ring coupled with the compensation provided by the radiofrequency (RF) cavities and technological solutions, including a top-up injection scheme and the optics design, would enable the FCC-ee to attain substantially more luminosity than any other proposed machine for center of mass collision energies of up to 400 GeV. At the heart of the FCC-ee lies an efficient superconducting (SC) radiofrequency (RF) system compensating for the 100 MW synchrotron radiation power losses in all modes of operation from 90 GeV up to 365 GeV. The major R&D topics include high-efficiency RF power production, SC cavity production, vacuum system components, beam instrumentation, new materials for beam collimation and dump systems. For the FCC-hh hadron collider, the key technology is high field O(16T) SC magnets with associated R&D lines in superconducting materials, both low- and high-temperature superconductors, and magnet design. A novel production method for superconducting could find applications in other accelerators beyond particle physics, as it optimizes the surface areas and thus simplifies the coating process and reduces the risk of slips that could reduce the cavity performance.

The results from the feasibility study will culminate in a feasibility report that should be ready by 2025/26 in time for the next update of the European Strategy. FCC-ee strives for developing innovative approaches in tackling some of the present challenges. However, it also gains confidence from the fact that the key 'ingredients' of the FCC-ee accelerator have already been demonstrated at one or several previous colliders or test facilities around the globe. A recent milestone, also demonstrating the collaborative nature of high-energy physics, has been the demonstration of some of the FCC-ee key concepts at the SuperKEKB collider in Japan. Specifically, a new world record luminosity of 3.12×10^{34} cm^{-2} s^{-1} was obtained earlier this June and a focusing world record $\beta_{\gamma}^{*} = 0.8$ mm was achieved in both rings.

The commitment and enthusiasm of the FCC community is indispensable for the success of the project along with a world-wide consortium of scientific contributors committed to the development and preparation of the FCC-ee science project from 2020 onwards. The realisation of the FCC relies on strong global participation and we welcome contributors in all areas of the study. If approved, the FCC will push the intensity and energy frontiers of particle accelerators and set the stage for the future of particle physics. Over the next five years, key events shaping the future of particle physics will unfold. Results from the next run of the Large Hadron Collider (LHC), and from other particle and astroparticle physics projects around the world will shape the future research agenda. These, along with the results of the ongoing R&D efforts on various domains and the completion of the feasibility study for a new research infrastructure at the heart of Europe will help us to chart the future scientific road map for the field of High Energy and Particle Physics.

How to characterize rocky Exoplanets: Ideas & Challenges

PT 7/2021

Lisa Kaltenegger, Cornell University

The discovery of more than 4500 extrasolar planets has revolutionized our understanding of how planetary systems form and given us a first glimpse into the large diversity of these new worlds. Most of these exoplanets (70%) have been discovered with the transit method, where the planet blocks part of the light from the star from our view with surveys from the ground as well as space missions like NASA's Kepler [1] and TESS (Transiting Exoplanet Survey Satellite) [2]–[5].

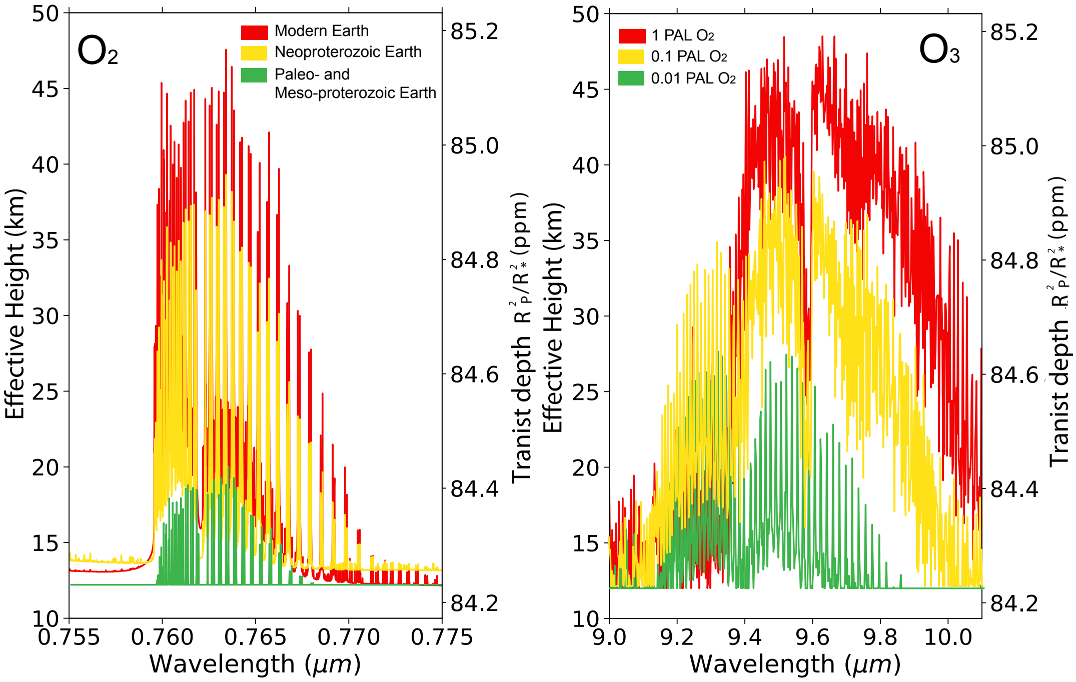
But while most extrasolar planets are hot planets orbiting close to their host star and have a large gas envelop, the first few dozen exoplanets e.g. [6]–[8] are small enough to be rocky like Earth e.g. [9], [10] and orbit in the so-called Habitable Zone (HZ) [11] of their host stars. Those exoplanets point to a large group of yet undiscovered planets that could potentially allow for liquid water on their surface.

The HZ is used as a concept that helps guide observations. It identifies the orbital distance region around one or multiple stars where liquid water could be stable on a rocky planet's surface similar to Earth (see e.g., [11]–[18]).

New estimates of the number of rocky planets in the HZ place it from 0.58 +0.73/-0.33 to 0.88 +1.28/-0.51 planets per star [19] for the empirical HZ. The limits of the Empirical HZ are set by the flux a young Mars and a young Venus received when there is no more evidence for liquid water on their surfaces [11]. The inner limit is not well known because of the lack of reliable geological surface history for Venus beyond 1 billion years ago.

Encoded in the planet's emergent and transmission spectra is information on the chemical makeup of a planet's atmosphere (e.g. review [10], [20]). The spectral database for 19 diverse planets and moons in our own Solar System [21] - available online – shows a wide variety of spectra that reflect differences of the Solar System objects. If the atmosphere is transparent, the emergent spectrum also carries some information about surface properties (e.g. [22]–[24]). That makes light a crucial tool to characterize exoplanets.

Our biosphere has modified our planet's atmosphere for billions of years, e.g. [25], [26], something we hope to find on other Earth-like planets soon. Thus, observing Earth could have classified it as a living world since the great oxidation event for a billion years already [27]–[29], through the buildup of oxygen in the presence of a reducing gas [30]–[35].



High-resolution (λ/Δλ > 100,000) spectra for the 0.76 μm O_2 (left) and 9.6 μm O_3 (right) feature showing the change due to the rise of oxygen from a Neoproterozoic Earth model with 0.01 present atmospheric level (PAL) of O_2, Paleo- and Meso-proterozoic Earth modeled with 0.1 PAL O_2 and modern Earth with 21% O_2 [45].

The presence or absence of spectral features will indicate similarities or differences between the atmospheres of terrestrial exoplanets and that of Earth, and their astrobiological potential (see e.g. [10], [32], [36]).

However, a comprehensive suite of tools will be needed to characterize habitable planets and moons because the mere detection of a rocky body in the HZ does not guarantee that a planet is habitable. It is relatively straightforward to remotely ascertain that Earth is a habitable planet, with oceans, a greenhouse atmosphere, global geochemical cycles, and life — if one has data with arbitrarily high signal-to-noise ratio (SNR) and spatial and spectral resolution. The interpretation of observations of exoplanets with limited SNR and spectral resolution as well as no spatial resolution, as envisioned for the first-generation instruments, will be far more challenging and implies that we will need to gather information on a planet's environment to understand what we will see at different wavelengths.

But what if we turn the question around and ask which stars in the solar neighborhood hold a vantage point to see Earth as a transiting exoplanet [37]–[40] and could identify its vibrant biosphere since early human civilizations [41]?

Evaluating the kinematics propagated through time using ESA's Gaia Mission early Data Release 3 (eDR3) [42] allows us to identify the stars with this special vantage point. 2034 stars in the Gaia Catalog of Nearby Stars (GCNS)[43] are in this so called Earth transit zone (ETZ) [39] in a time window of +/-5'000 years (data available at *https://github.com/jfaherty17/ETZ*). 313 objects were in the ETZ in the past, 319 will enter the ETZ in the future, and 1402 have been in the ETZ for some time. Among these stars are 7 known exoplanet hosts that hold the vantage point to see Earth transit, including Ross-128, which saw Earth transit in the past, Teegarden's Star, and Trappist-1, which will start to see Earth transit in 29 and 1642 years, respectively. Given that Earth began transmitting radio waves into the solar neighborhood about 100 years ago [44], we found that human-made radio waves have swept over 75 of the closest stars (within 30 pc) on our list already.

The search for rocky planets has already revealed a fascinating diversity of worlds, and with the upcoming generation of telescopes like the JWST (launch 2021) and the ELTs (ELT observation to start in 2027), we will be able to explore such worlds remotely. We can probe for signs of life, pushing the limit of technical capabilities. Any information we collect on habitability is embedded in a context that allows us to interpret what we find. To search for signs of life, we need to understand how an observed atmosphere physically and chemically works. Observations of rocky exoplanets will give us insights into these fundamental questions, improving our understanding of how habitable worlds function and giving us a first glimpse onto other potentially habitable worlds.

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Science and its Publics: the Case of Physics

PT 8/2021

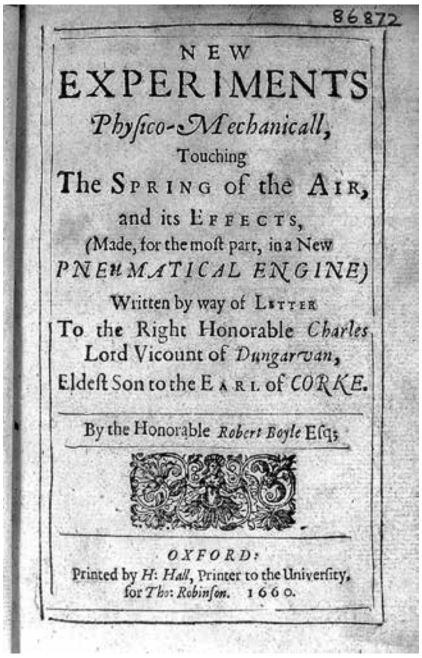
Martina Merz, University of Klagenfurt

How scientists should interact with the public is a widely and, at times, controversially discussed topic. The debate typically builds on the idea of a sharp contrast between science and its publics. Such strict separation, however, has not always existed and it also may be bridged. The relation between science and its publics has undergone significant transformations. Throughout the centuries, science's actors and practices have faced various publics at specific sites and with different concerns. This text will trace some of these transformations in the form of four short sketches. Drawing on selected studies in the history of science, each presents a case history associated with physics. To keep this text short, only a few contrasting cases will be discussed, and the focus will be on differences between them.

Gentlemanly Public of Science in 17th Century England

In the 17th century, naturalists such as Galileo, Kepler, Boyle, and Pascal proclaimed a 'new science.' They presented their findings' novelty as a radical break with the past – a development which would later become known as the 'scientific revolution.' The naturalists lived and worked in different social environments, which formed specific publics for the new science. In England, the milieu of gentlemen was of outstanding importance for natural philosophy, as Steven Shapin and Simon Schaffer show in their seminal work on the controversy between Thomas Hobbes and Robert Boyle [1, 2].

Modern empiricism was based on the conviction that scientific knowledge is grounded in, and can only be derived from, direct and unmediated sensory experience. In addition to observing natural phenomena, the production of experiential facts through experiments gained particular importance, especially at the Royal Society of London. The vacuum pump developed by Robert Hook, Boyle's assistant, became to determine the generally accepted procedure for experimental natural philosophy (see Figure 1). Corresponding experiments were repeated throughout Europe.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NEW
EXPERIMENTS
Phyſico-Mechanicall,
Touching
The SPRING of the AIR,
and its EFFECTS,
(Made, for the moſt part, in a New
PNEUMATICAL ENGINE)
Written by way of LETTER
To the Right Honorable *Charles*
Lord Vicount of *Dungarvan*,
Eldeſt Son to the EARL of *CORKE.*

By the Honorable *Robert Boyle* Eſq;

OXFORD:
Printed by *H: Hall*, Printer to the Univerſity,
for *Tho: Robinſon.* 1660.

Figure 1: Front page of the publication by Robert Boyle (1660) on his experiments with vacuum pumps. No known copyright.

If, as the empiricists claimed, knowledge is grounded in unmediated experience, the question arises by which procedures shared knowledge can be collectively generated. In other words, how do individual statements become public? At the Royal Society of London, the answer to this question consisted of naturalists conducting experiments in front of an audience of carefully picked observers in the form of public demonstrations. Selected observers vouched as witnesses, i.e., by the act of their public testimony, for the correctness of the results produced in the experiment, which they were also required to confirm in writing. The most important selection criterion for naming witnesses was their status as 'gentlemen.' Whether witnesses had scientific or technical skills was secondary. Gentlemen stood for the trustworthiness of scientific results thanks to their culture of honor (reliability, honesty) and their high social status. The gentlemen were not merely a distant or peripheral public to the conduct of experiments. Instead, the men were crucial as they contributed to the securing of knowledge and enabled findings to circulate while retaining their credibility.

Electricity, a Public Science in the 18th Century

In contrast to the discussed exclusive events and privileged sites such as the Royal Society of London (or the Court of the Medici in the case of Galileo), a second case concerns the early days of electricity in the context of German enlightenment. In this historical context, a variety of less secluded public sites and corresponding publics appeared.

In his historical study, Oliver Hochadel [3] is interested in the diversity of electrical practice in places as diverse as the inn, the fair, the school, the instrument maker's workshop, or the Hetztheater in Vienna. Hochadel deliberately employs a broad notion of electrical practice not limited to the activities of researchers (in contrast to amateurs) or serious work (in contrast to entertainment). The reason is that, at the time, such distinctions did not carry the weight they would later. The status of the sciences was still open to interpretation. Electricity was a 'public science' in the sense that knowledge was generated and controversially debated in a variety of publics and with competing explanations. Electrical phenomena were also presented in the form of public spectacles. A technical setup to electrify whoever was willing to undergo such an experiment is presented in Figure 2.

Figure 2: Electrifying for 1 Schilling („Elecktrisiren für 1 Schilling"), Aquatint etching, Hamburg, 1806/08. Copyright: akg-Images

Disciplinary Publics in the 19th Century

In the 19th century, scientific institutions developed a clear separation from the lay public. This development occurred in the wake of the emergence of scientific disciplines, which brought about two types of publics, namely 'inner' and 'outer' publics. The disciplinary structure of science, higher education, and universities became institutionalized since the late 18th century, first in Germany and then in other European countries [4, 5]. Rudolf Stichweh (ibid.) characterizes a scientific discipline by joint problems, methods, theories, and a shared body of knowledge; a scientific community; disciplinary study programs and careers; professional societies and publication organs (especially journals). Thus, a number of structurally similar disciplines formed.

The emergence of disciplinary communities went hand in hand with a change in scientific practices and values. Scientific work became associated with the idea of research, i.e., a preference for novelty and the continuous production of new knowledge. At the same time, there was increasing specialization in terms of research problems, methods and instruments, and theoretical approaches. The scientific laboratory became the central place of knowledge production in physics and chemistry. These changes meant that scientific life increasingly took place within the boundaries of disciplinary structures, whether intellectual, institutional, or physical. In this way, the disciplinary community became the dominant public sphere for scientific work with its laboratories, conferences, study programs, and journals.

The separation of science from its non-scientific environment accompanied this development. Earlier public spheres of science thus lost their importance. Professional activity and academic research or university teaching positions became increasingly mutually exclusive, while they had been compatible in earlier times. And amateur science, which had still been very widespread and well-regarded in the 18th century, also lost prestige. In the course of the institutionalization of science, the scientific disciplines thus reconstituted their publics by distinguishing 'inner' and 'outer' publics.

Image of the Ignorant Public in the 20th Century

The concept of modern science includes the notion of an existing 'gap' between science and the public (corresponding to the previously discussed separation of science). However, this does not imply that public knowledge must also be devalued. This devaluation, in fact, is of recent date and differs from the conception of earlier epochs, as Bernadette Bensaude-Vincent [6] argues. She has analyzed how scientists view the public and imagine their relationship with it. Whereas an enlightened amateur public in the 18th century and public science in the 19th century had still enjoyed broad recognition, this was no longer the case in the second half of the 20th century. The public came to be imagined as "a mass of gullible, irrational, and ignorant people" [6, p. 106]. This notion resonates with the 'deficit model' of science communication, according to which the science's public is deficient and in need of a remedy for the defect.

Where Do We Stand Today?

Figure 3: Dans la peau d'un chercheur, visite au physiscope. CERN-GE-1105151-45. Copyright: CERN

The idea of an ignorant and thus deficient public still informs many contemporary activities of science communication. Very often, these do not take sufficient account of the fact that we are not dealing with a homogeneous group, but with publics (in the plural) with very different demands, interests, knowledge, and experiences (see children visiting the Physiscope at the University of Geneva in Figure 3). At the same time, an increasing number of initiatives have emerged in recent years that focus on public participation (e.g., under the label 'citizen science') rather than merely on knowledge dissemination. With many physics laboratories devising outreach programs, important questions arise. For example: How can physics be made public in participatory projects – and to what effect? Who should take responsibility for interacting with the public(s): expert communicators, a few selected physicists, or all researchers alike – and on what ground? Is there something to gain for physics research or teaching as well? And, finally, what role should physicists and their institutions play in scientific controversies that receive broad public attention?

Acknowledgment

This text includes selected material in an abridged form published previously in German by the same author: M. Merz, Die Entwicklung der Wissenschaften im Lichte ihrer Öffentlichkeiten. Pp. 31-39 in: R. Neck & C. Spiel (eds.), *Wissenschaft und Aberglaube* (Böhlau, Wien, 2020).

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Neuer SPG Preis für Arbeiten mit Bezug zur Energietechnik

Nouveau prix de la SSP pour des traveaux faisant référence au domaine des technologies énergétiques

Hitachi Energy (*www.hitachienergy.com*) stiftet ab dem Jahr 2022 einen SPG Preis, der jährlich für eine ausserordentliche Forschungsarbeit mit Bezug zur Energietechnik verliehen wird.

Hitachi Energy ist ein weltweit führendes Technologieunternehmen, das insgesamt auf eine fast 250-jährige Geschichte zurückblicken kann und rund 38’000 Mitarbeiter in 90 Ländern beschäftigt. Das Unternehmen mit Hauptsitz in der Schweiz bedient Kunden aus den Bereichen Energieversorgung, Industrie und Infrastruktur über die gesamte Wertschöpfungskette hinweg sowie aufstrebende Bereiche wie nachhaltige Mobilität, intelligente Städte, Energiespeicherung und Datenzentren. Hitachi Energy verfügt über eine nachgewiesene Erfolgsgeschichte, eine globale Präsenz und eine beispiellose installierte Basis. Das Unternehmen bringt soziale, ökologische und wirtschaftliche Werte in Einklang und engagiert sich mit bahnbrechenden und digitalen Technologien als Partner der Wahl für eine nachhaltige Energiezukunft, um ein stärkeres, intelligenteres und umweltfreundlicheres Netz zu ermöglichen.

Die nachhaltige, ressourcenschonende, klima- und umweltfreundliche Gewinnung, der Transport, die Verteilung, und Nutzung von Energie für eine zukünftige, sozial gerechte globale Verteilung des Wohlstandes ist eine der grossen Herausforderungen unserer Zeit. Der von Hitachi Energy gestiftete und von der SPG verliehene Preis soll exzellente Arbeiten mit physikalischem Hintergrund würdigen, die einen Bezug zur Energietechnik haben und deren Resultate das Potenzial beinhalten, zu Lösungen der Energieproblematik beizutragen. Wir möchten damit unsere Wertschätzung diesbezüglicher Anstrengungen und Erfolge kreativer junger Forscherinnen und Forscher auf Schweizer Hochschulen bekunden, und hoffen, damit einen kleinen Beitrag zur Motivation von Wissenschaftlerinnen und Wissenschaftlern zu leisten, ihre Talente auf diesem für die Zukunft zentralen Gebiet einzusetzen.

À partir de 2022, Hitachi Energy (*www.hitachienergy.com*) financera un prix de la SSP qui sera décerné chaque année pour récompenser des travaux de recherche exceptionnels faisant référence au domaine des technologies énergétiques.

Hitachi Energy est une entreprise technologique mondiale de premier plan, forte d'une histoire de près de 250 ans et comptant environ 38 000 employés dans 90 pays. Basée en Suisse, la société sert des clients des services publics, de l'industrie et des infrastructures sur l'ensemble de la chaîne de valeur, ainsi que dans des domaines émergents tels que la mobilité durable, les villes intelligentes, le stockage de l'énergie et les centres de données. Hitachi Energy dispose d’une expérience avérée, d’une présence au niveau mondial ainsi que d’une infrastructure inégalée. L'entreprise aligne ses valeurs sociales, environnementales et économiques et s'engage à être le partenaire de choix pour un avenir énergétique durable grâce à des technologies révolutionnaires et numériques, permettant un réseau plus fort, plus intelligent et plus vert.

La production, le transport, la distribution et l'utilisation de l'énergie de manière durable, efficace en termes de ressources, respectueuse du climat et de l'environnement, pour une future répartition mondiale des richesses socialement juste, est l'un des grands défis de notre époque. Le prix, parrainé par Hitachi Energy et décerné par la SSP, vise à récompenser d'excellents travaux de physique liés à la technologie de l'énergie et dont les résultats sont susceptibles de contribuer à la résolution du problème de l'énergie. Nous tenons à exprimer notre reconnaissance pour les efforts et les succès des jeunes chercheurs créatifs des universités suisses à cet égard, et espérons apporter une petite contribution pour motiver les scientifiques à utiliser leurs talents dans ce domaine essentiel pour l’avenir.

In Memoriam Ingo Sick

Ingo Sick, Prof. Dr. Dr. h. c. of the University of Basel, passed away on 30 May 2021, two days after his 82nd birthday. During his postdoctoral period at Stanford University with Nobel Prize winner Robert Hofstadter, he experienced the beginnings of electron research with the world's best electron accelerator at the time, SLAC. This domain of research was to remain with him forever.

Ingo Sick then spent several years doing research at CEN Saclay. In 1987, he and Bernard Frois were awarded the Bonn Prize "*For their elegant studies of nuclei using high-energy electron scattering. In particular, their precision measurements of nuclear charge and current densities have offered novel perspectives on ground states and valence orbitals. Their studies of few-nucleon systems have demonstrated the need for sub-nucleon degrees of freedom in a complete description of the nucleus. This body of work has provided firm benchmarks against which to test our understanding of the nuclear many-body problems* (citation from the laudation)." Indeed, Ingo's measurements of the electromagnetic structure of light few-body nuclei, including determination of the proton, deuteron, helium-3, and hydrogen-3 elastic form factors, still set a standard in the field today.

In 1983 Ingo Sick became associate professor in Basel and in 1993 full professor of experimental nuclear physics at the Department of Physics of the University of Basel until his retirement in 2004. For many years he was a research councilor and member of the Foundation Council of the Swiss National Science Foundation. In 1988 Ingo Sick was awarded an honorary doctorate from Utrecht University for his services to NIKHEF.

Ingo Sick was active and successful in a broad field of electron scattering exploring the structure of nucleons and light nuclei. He developed an unerring instinct for data analysis and experimental techniques. Early on he recognized the advantages of double polarization experiments due to the amplification of small fractions in the nucleon-nucleon interaction by interference of the wave functions leading to a reduction of systematic errors by measuring asymmetries instead of absolute cross sections. This resulted in several measurements of the electric form factor of the neutron at MAMI, Mainz, and at Jefferson Lab, Virginia, to whose nuclear physics program he contributed significantly, in particular to the Hall C experiments "$x > 1$" and the investigation of short-range correlations in the nucleon-nucleon interaction using quasi-elastic (e,e'p) scattering experiment off C, Al, Fe and Au nuclei. In the latter experiments the so-called spectral function was extracted, showing that the “missing strength” of the valence proton orbitals is shifted to larger excitation energies and higher proton momenta, significantly increasing towards the heavy nuclei. This still remains a hot topic not only at Jefferson Lab and its interest is reflected in many theoretical works all over the world.

Ingo Sick was also active at the Paul Scherrer Institute, where, together with Jürg Jourdan and several doctoral students and postdocs from Basel, he conducted experiments in the NE-C on the spin-dependent part of the nucleon-nucleon potential exploiting polarised protons from Injector I and neutrons from secondary reactions. He strongly advocated that the Injector I cyclotron should not be shut down, which indeed did not happen until after his retirement. Later, Ingo Sick was very interested in the measurements on muonic hydrogen (*https://indico.psi.ch/event/4512*), which were performed on a beamline at the meson production target E of PSI's high intensity proton accelerator HIPA facility, resulting (A. Antognini et al. *Science* **339**, 417-420 (2013)) in 4 % smaller proton radius than from electron scattering. This discrepancy is still not fully understood. Or in Ingo's words, "Many of the ideas that have been stated have all been looked at in more detail. Nobody has come up with a clear result. The idea of fundamental differences between muons and electrons is sort of hard to imagine" (*https://doi.org/10.1038/nature.2013.12289*).

Ingo was not only active in experimental nuclear research, but also collaborated with numerous theorists. In total he published over 300 papers, many with substantial contribution from him. Ingo Sick was relentless in physics, always searching for the truth. Due to his vast experience with experiments, he immediately recognized when something was not going right and could even give the right advice by remote diagnosis. He was gentle and full of good advice to his doctoral students, postdocs, postdoctoral researchers and staff. We all enjoyed his parties with good wine and meat roasted over the fireplace, the annual asparagus dinners in France and his conversations, peppered with humor and charm as well as a portion of self-irony.

We'll miss Ingo.

Daniela Kiselev (ASA/GFA)

Jürg Jourdan, Bernd Krusche, Friedrich-Karl Thielemann, Dirk Trautmann (University of Basel)

Adrian Honegger, representing all the former doctoral students, postdocs and habilitation students of Ingo Sick

Progress in Physics (84)

AMS-02, the Cosmic Ray Observatory

10 Years on the International Space Station

Martin Pohl

Abstract

The Alpha Magnetic Spectrometer (AMS-02) has been up and running on the International Space Station ISS since May 2011. The structure of the detector is similar to a scaled-down version of modern collider experiments. Its components were mostly constructed in Europe, integrated and calibrated at CERN. AMS registers and measures cosmic rays in near-earth orbit and has so far collected over 175 billion particles. Commensurate with these unique statistics, the requirements for systematic precision are high. The results of the experiment shed new light on the origin and transport of cosmic particles on their way from their sources to our Solar system. In addition to more or less conventional astrophysical phenomena, dark matter or small pockets of antimatter may contribute. After replacement of the cooling system, which posed completely new challenges for NASA, the experiment is now equipped to take data for as long as the ISS stays operational.

(Credit: NASA)

1 Cosmic Rays

Cosmic rays are high-energy, electrically charged particles which originate from cosmic and astrophysical phenomena. Most of them come from our Milky Way. When they hit the Earth's atmosphere with an intensity of around one particle per cm^2 and second, they have a long journey behind them. Guided by magnetic fields and in interaction with interstellar gas and plasma, they diffuse through our galaxy for tens of millions of years. More than 100 years after their discovery, the physics of cosmic ray sources and their voyage to us is still full of puzzles.

After Victor Franz Hess discovered the extraterrestrial origin of "atmospheric electricity" during his balloon flights in 1912 [1], experiments were carried out at ever increasing altitudes in the decades that followed. Figure 1 summarizes the ionization rates measured as a function of altitude, from manned and unmanned balloon flights before and after the First World War. Werner Regener and his student Georg Pfotzer were pioneers in the use of weather balloons with automatized Geiger-Müller counters in the 1930s. They measured the flux of cosmic particles – their number per unit area and time – as a function of altitude and compared it with the ionization rate. Both have the same altitude dependence, so it is in fact individual charged particles that trigger "atmospheric electricity". The results of these unmanned flights were hardly known beyond a small circle of experts. In contrast, the manned stratospheric flights by Auguste Piccard and Max Cosyns attracted unprecedented public attention. Thirty thousand spectators and numerous media watched the start of his balloon flight from the military airport of Dübendorf near Zürich, shown in Figure 2. A battalion of the Swiss Army held back the balloon and its aluminum capsule while it was being filled. The two "conquerors of the stratosphere" became public heroes in Switzerland and Belgium, Piccard was immortalised by Hergé as Pro-

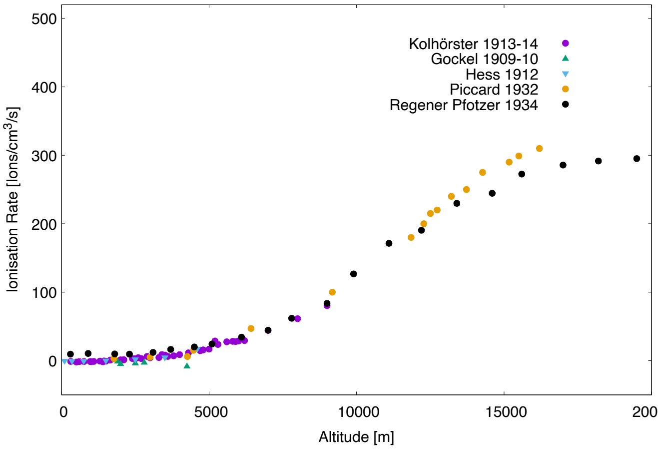

Figure 1: Ionization rate as a function of altitude above sea-level [1], measured during manned balloon flights by A. Gockel, V. F. Hess, W. Kohlhörster and A. Piccard. E. Regener and G. Pfotzer reached even greater altitudes with unmanned weather balloons.

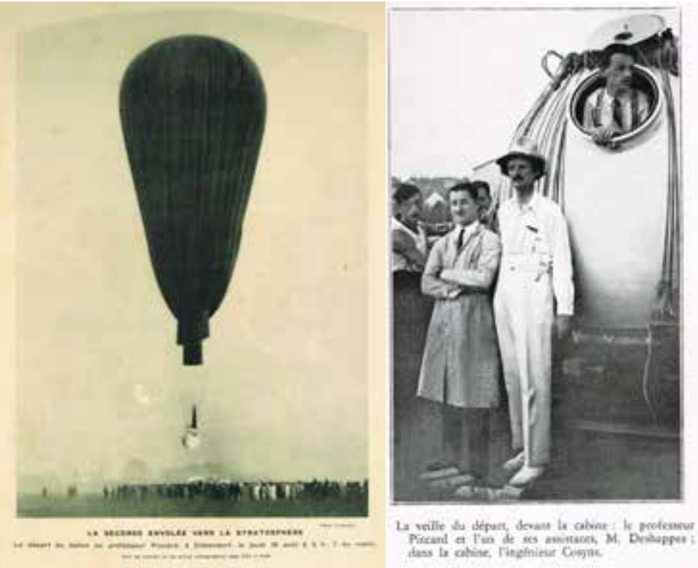

Figure 2: Left: Photo from the title page of the French magazine "L'Illustration" of August 27, 1932, showing the lift-off of Auguste Piccard's stratospheric mission from Dübendorf. Right: Auguste Piccard in front and Max Cosyns inside the pressurised aluminum capsule, from the same issue of "L'Illustration". (Credit: Author's collection)

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[1] For early Swiss contributions to this discovery, see e.g. J. Lacki, "Albert Gockel: from atmospheric electricity to cosmic radiation", *SPG Mitteilungen* 38 (2012) 25-29

fessor Calculus (professeur Tournesol in the original) in the famous "Adventures of Tintin" comics. Regener, whose balloon launches from the courtyard of his Stuttgart institute were only witnessed by his colleagues and students, was pushed out of his academic position by the Nazi regime. Today he is considered one of the pioneers of geophysics.

At altitudes of around 20 km, the rate of ionization by cosmic rays reaches the so-called Regener-Pfotzer maximum and then decreases. James Van Allen took the first measurements outside the Earth's atmosphere in 1947 with a V2 rocket confiscated during the occupation of Germany. He found that the counting rate plateaued beyond about 50 km altitude, at about half of its maximum level. He was probably the first who actually observed mainly primary cosmic radiation, and not particles released in cosmic atmospheric showers. Subsequently, especially during the geophysical year 1958 with the Explorer and Pioneer missions, Van Allen discovered the Earth's radiation belts named after him – geomagnetic regions in which secondary particles of cosmic radiation are trapped like in a magnetic bottle. He can thus be considered the pioneer of cosmic ray research in space. In the following decades, measurements in space were continued with the Soviet Proton and Sokol missions.

From the observations at great altitudes, a kind of consensus model has emerged in the last few decades, which qualitatively summarizes the gross features of cosmic rays in the energy range up to a few 10^6 GeV:

- This radiation comes mainly from supernovae in the Milky Way, so it consists of stellar material, atomic nuclei [8, 9] and electrons. The sources are randomly distributed in the galaxy. The density and rate of supernovae are large enough to explain the observed energy density of cosmic rays.

- The acceleration of individual particles to high energies takes place in plasma shock waves, which emerge from supernovae. The so-called Fermi mechanism causes the particle flux Φ – defined as the number of cosmic rays per unit area, time and solid angle – to follow a power law as a function of energy. The differential flux $d\Phi/dE$ indicates the particle flux per energy interval. It decreases like $d\Phi/dE \propto E^{-\gamma}$, with the so-called spectral index γ, a term borrowed from spectroscopy of electromagnetic radiation. A larger index corresponds to a softer spectrum, a smaller index to a harder one. One expects $\gamma \simeq 2$ at the source for all particle species with unit charge.

- The particles then diffuse through the material and plasma of the Milky Way and remain stored in the galaxy for tens of millions of years. They are thoroughly swirled so that directional information is lost. The result is a roughly isotropic and homogeneous interstellar particle flux.

- Particles lose energy in this process and the spectral index increases by about 0.7 for nuclei, and 1 for electrons and positrons, which lose energy more easily. In the Solar system one thus expects $\gamma \simeq 2.7$ for primary nuclei and $\gamma \simeq 3$ for primary electrons.

- Through interaction with interstellar matter secondary particles are produced. The spectra of these secondaries are softer, since they result from inelastic scattering, i.e. they have a larger spectral index. However, their spectral index should increase by the same amount $\Delta\gamma$ with respect to primaries for all secondary species.

Direct observation at high altitudes is so far limited to energies up to a few TeV, since balloon and space missions do not allow very large detectors. Higher energies have only been accessible to indirect observation via atmospheric showers. As an example, Figure 3 shows the fluxes of selected nuclei and the only definitely detected antinucleus $\overline{\mathrm{H}}$. As one can see in the double logarithmic plot, the differential particle fluxes do decrease with energy according to a power law, by almost three orders of magnitude per energy decade above 10 GeV. The fluxes of the few electrons and positrons drop even more steeply. The counting rate of an experiment – and thus its range in terms of energy – is determined by the acceptance, which roughly corresponds to the product of its area and the solid angle covered. The exposure time is of course also decisive for the overall statistics.
Figure 3 shows how the results of AMS-02 cover this research field in the energy range up to a few TeV. What cannot be appreciated in this representation is the far superior accuracy of AMS results compared to previous experiments. Spectra and composition contain information about production, acceleration and transport mechanisms, but details re-

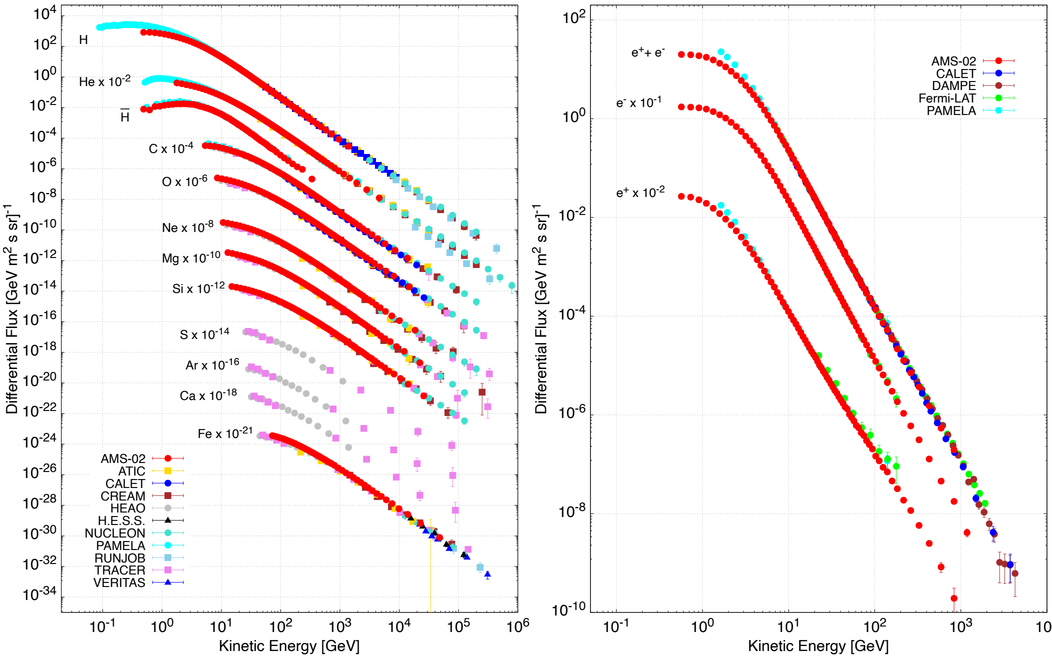


Figure 3: Differential flux of cosmic nuclei and anti-nuclei (left), electrons and positrons as well as the sum of the two (right), as a function of their total kinetic energy. Results of selected balloon experiments are represented with squares (■), space experiments with points (●), atmospheric shower experiments with triangles (▲) [1]. Most error bars, especially for AMS results, are smaller than the symbol size.

main hidden in a double logarithmic plot. And it is precisely the details that provide information about astrophysical phenomena important for cosmic rays.

2 The AMS Project

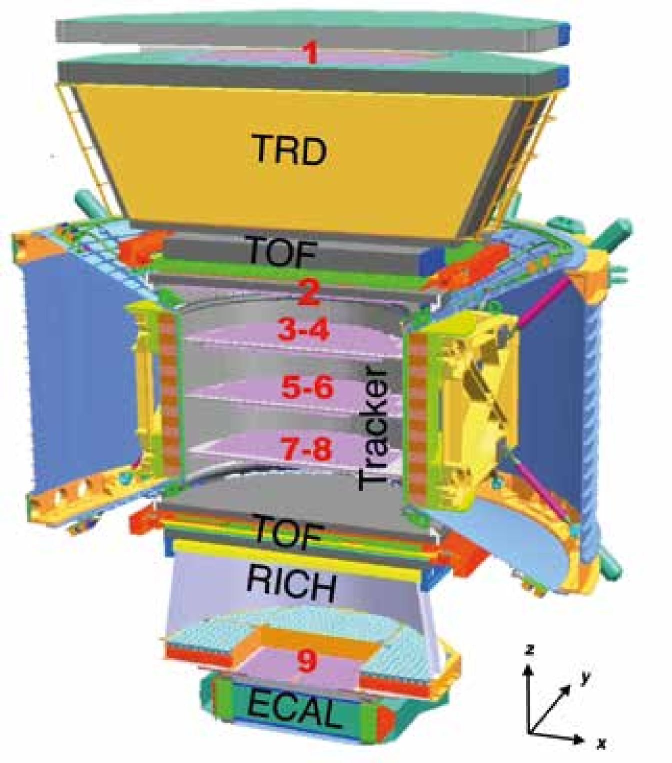
Complex detector systems, as we know them from accelerator particle physics, are a relatively new resource in cosmic ray research. One of the reasons is that conditions prevail during a balloon flight, and even more so during a rocket launch, that few detectors survive unscathed [2]. In orbit, very technology-hostile conditions reign in terms of temperature fluctuations and radiation exposure. Space experiments which meet the requirements of a typical collider experiment are therefore as rare as opportunities to fly them.

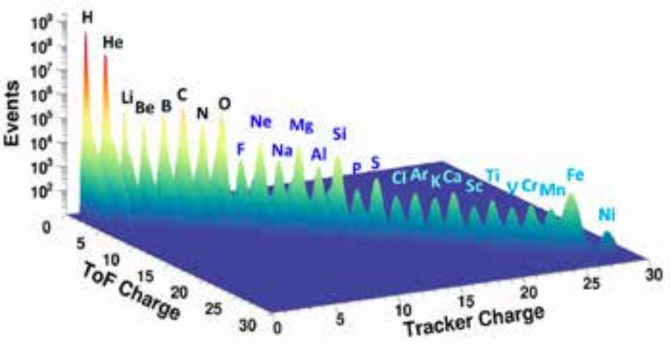
In a magnetic spectrometer, charged particles are directed onto a curved path by a magnetic field. The radius of curvature determines the magnetic rigidity $R = p/Z$, the ratio of momentum p and electric charge Z. To do this, one needs a magnet with a precisely known field and track detectors to measure the path of the particle. A pioneer in the field of space-based spectrometers was the PAMELA experiment of the WiZARD collaboration, which relied on long experience with balloon and collider experiments alike. Modern technology and analysis methods from particle physics at accelerators thus found their way into the systematic research of cosmic rays [3].

In 1994, Samuel C. C. Ting proposed to build a spectrometer with a hundred times greater acceptance and a complete set of detectors for particle identification, to be acommodated on the International Space Station ISS. The proposal was enthusiastically supported by NASA under Dan Goldin, Administrator from 1992 to 2001. The project was named Alpha Magnetic Spectrometer (AMS), after the code name “Alpha Station” for one of the numerous iterations of the ISS concept. The international collaboration, responsible for construction and operation of AMS, today includes around 500 scientists and engineers from 56 institutions in 16 countries. The dimensions of AMS with (5 × 4 × 3) m^3 and a weight of 7.5 t are adapted to the capacity of the now historical space shuttle (Space Transport System STS).

The diagram on the right shows a section through the AMS detector. A cylindrical permanent magnet generates a dipolar magnetic field of about 0.15 T. Its direction is horizontal in the x direction. Particles enter from above, moving in the $-z$ direction. The nine tracking layers (Tracker 1– 9), silicon strip detectors with high resolution and double-sided read out, each locate the particle passage in the bending (y) and non-bending direction (x). They also measure the absolute value of the particle charge.

The tracker is embedded in a set of detectors for particle identification, which complement each other and increase systematic reliability. A transition radiation counter (TRD) differentiates between light and heavy particles. Four layers of time-of-flight scintillators (TOF) determine the direction of flight, velocity and charge. The ring-imaging Cherenkov detector (RICH) also determines velocity and charge. Finally, an electromagnetic calorimeter (ECAL) measures the energy of electrons, positrons and photons and distinguishes them from hadrons. The absolute value of the electrical charge is determined by practically all detectors with different resolutions. Details about the detector and its performance can be found in a comprehensive report [7].





Redundancy of measurements – for energy/momentum, velocity and electrical charge – is a key strength of the AMS detector. As an example, the plot above shows the nuclear charge measured in the TOF system against the one obtained from the tracker sensors.

The track detector produces around 140 W of heat inside the magnet bore. In order to keep the temperature of the spectrometer constant, two-phase cooling with liquid CO_2 transports the heat to the outside, where it is dissipated by radiators. Its four redundant pumps showed signs of wear and tear since 2015, and a replacement was necessary for long-term operation. An improved replacement cooling system was thus sent to the ISS, along with specially developed tools. In a complex operation in January 2020, the exchange was accomplished during four space walks. This was the first time that a high-pressure system was cut open in space and re-welded, arguably the most challenging operation since the repair of the Hubble telescope.

NASA initially required a pilot experiment in the cargo bay of a shuttle to ensure the feasibility of the design and the capabilities of the collaboration. This prototype detector, called AMS-01, flew aboard Space Shuttle Discovery in June 1998 on the last American mission to the Russian space station MIR. In ten days the experiment registered about 70 million cosmic particles [4].

Based on this success, the collaboration decided to build a more ambitious detector, AMS-02, for long-term measurements on the ISS. It was initially intended to replace the permanent magnet with a more powerful superconducting electromagnet [5]. The majority of detector components was produced in Europe. The entire detector was integrated with the electromagnet at CERN in 2009 and calibrated in CERN particle beams. AMS is an excellent example of how CERN technology, expertise and infrastructure helps projects in neighbouring fields to succeed. Consequently, it was the pioneer of a new category of projects at CERN, the so-called recognised experiments, which by now has many prominent members [6].

When testing the thermal properties of AMS in vacuum at ESA-ESTEC in the Netherlands, it turned out that the 2500 l supply of superfluid helium for cooling the magnet would only allow operation for about two years, too short for the planned research program. Since an in-orbit refill was deemed unfeasible, the electromagnet was abandoned and the detector adapted to the permanent magnet of AMS-01. The Info Box describes the final detector.

However, the installation on the ISS was anything but guaranteed for several years. After the accident of space shuttle Columbia in 2003, in which seven astronauts lost their lives, NASA decided to reduce the space shuttle program and discontinue it by 2010. Many flights were removed from the flight schedule, including the one for AMS. Sam Ting, however, organised support from influential US senators. In 2008, both houses of parliament passed a budget law which required NASA to transport AMS-02 to the ISS. In January 2009, three days after President Obama took office, AMS-02 was back on the flight schedule, with an additional shuttle flight STS-134.

On August 26, 2010, AMS-02, carefully recalibrated, was transported from CERN to Kennedy Space Center. After installation in the cargo bay, it was launched on May 16, 2011 with the last mission of space shuttle Endeavor. Three days later, robotic arms transported the detector to its anchor point on the starboard side of the ISS transverse truss. A few hours later, AMS-02 registered the first helium nucleus. The photo at the begin of the article shows AMS-02 in position. The results of the first seven years on the ISS have recently been summarized [7]. A few highlights are presented below.

3 Cosmic Nuclei

The analysis of cosmic ray composition affords us a look into the cosmic nuclear physics laboratory, and its functioning from shortly after the Big Bang until today [8, 9]. Hydrogen and helium nuclei originate mainly from bario- and nucleosynthesis a few minutes after the Big Bang [10]. The ratio of their abundances is indeed one of the pillars of Big Bang theory. Like all other nuclei, they are accelerated to high energies by turbulent magnetic fields, such as those found in shock waves following supernovae. Since this is a magnetic mechanism, the magnetic rigidity $R = p/Z$ (measured in Gigavolts, GV) is the suitable variable for describing their spectra.

Significant deviations from a simple power spectrum are already evident in the dominant components. Figure 4 shows the proton spectrum as an example, multiplied by $R^{2.7}$ so that details can be seen on a linear scale. Above about 200 GV, the spectrum becomes significantly harder. Calorimetric measurements confirm this trend.

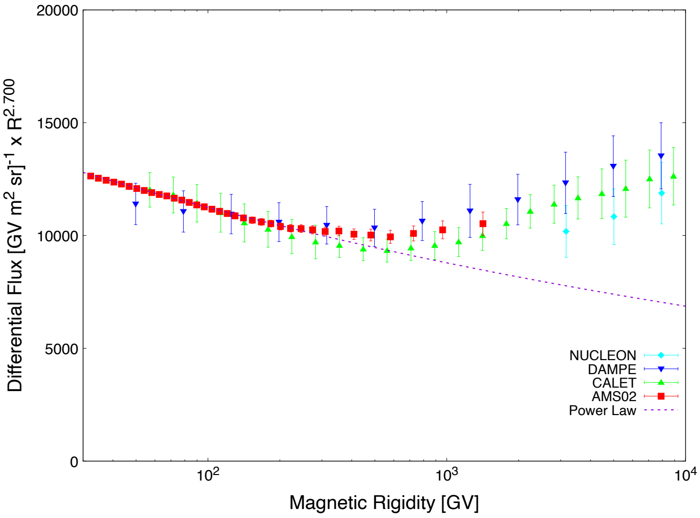


Figure 4: Differential flux of protons as a function of the magnetic rigidity R, scaled with $R^{2.7}$, from recent measurements by space experiments [1].

Light nuclei such as lithium, beryllium and boron come at most partially from primordial nucleosynthesis. They are raw materials and intermediate products in the breeding of heavier nuclei inside stars, and therefore strongly underrepresented in stellar matter. They are found three orders of magnitude more often in cosmic rays, thanks to the splitting of heavy nuclei by spallation on the way from their source to us. Stable primary products of stellar nucleosynthesis – such

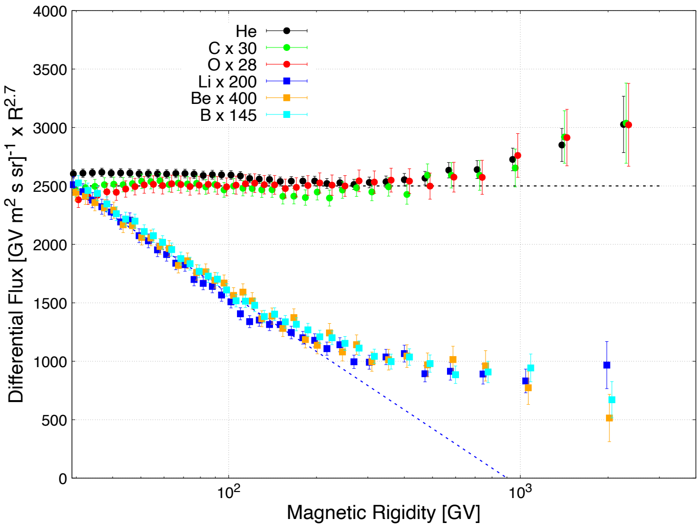


Figure 5: Differential flux (times $R^{2.7}$) as a function of magnetic rigidity for primary nuclei (He, C, O) and secondary products of interactions with interstellar matter (Li, Be, B) [7]. The fluxes from AMS-02 are scaled so that they roughly match the helium flux at low energies. The lines indicate the dependency expected with a constant spectral index.

as helium, carbon or oxygen, even iron – all show roughly the same power spectrum, although their abundance decreases drastically with increasing mass. Secondary spallation products, on the other hand, have a significantly softer spectrum, as shown in Figure 5.

Surprisingly, however, all nuclei show a change in the spectral index at a rigidity of around 200 GV [7]. The change towards a harder spectrum is $\Delta\gamma_{\mathrm{HeCO}} = +(0.170 \pm 0.015)$ for the lighter primary nuclei helium, carbon and oxygen. It is a little less pronounced for the heavier primaries neon, magnesium and silicon, with $\Delta\gamma_{\mathrm{NeMgSi}} = \Delta\gamma_{\mathrm{HeCO}} - (0.045 \pm 0.008)$. For secondary nuclei the change in spectral index is much more pronounced, with $\Delta\gamma_{\mathrm{LiBeB}} = \Delta\gamma_{\mathrm{HeCO}} + (0.140 \pm 0.025)$. It is not entirely clear where this turn to a harder spectrum comes from. In principle, new sources or stronger "accelerators" in the vicinity of our solar system can cause this phenomenon. However, the fact that the spectral index change is almost twice as large for secondaries compared to primaries indicates a transport effect [11]. The diffusion through the galactic disk could, for example, run differently than in the halo of the Milky Way [12]. The smaller difference between light and heavy primaries may indicate other spatial inhomogeneities in cosmic ray diffusion [13, 14], since heavier particles propagate shorter distances [15]. But these are not the only astrophysical phenomena which may be invoked to explain the unexpected deviations from the simple consensus model [16].

All this new information has to be incorporated into models such as the GALPROP code [17], which quantitatively describe the release, acceleration and diffusion of cosmic rays in the Milky Way. All available data from astrophysics, nuclear and particle physics are used to understand the formation and transport of particles from their sources to us. Precision results like those from AMS have already had a major impact on these models and will continue to do so. Only when the contributions of conventional astrophysical phenomena to cosmic radiation are understood with sufficient accuracy can potential contributions from unconventional sources – such as dark matter – be firmly established.

4 Cosmic Antimatter

But uncertainties of this kind don't really deter from the search for unconventional phenomena, especially since the energy density of dark matter considerably exceeds that of normal matter. In a search for unconventional sources of cosmic radiation, components which rarely come from normal astrophysical processes are particularly suitable. The total rate of antihydrogen nuclei $\overline{\mathrm{H}}$, for example, is suppressed by more than four orders of magnitude with respect to hydrogen. Conventionally, antiprotons come from the production of baryon-antibaryon pairs in interactions of the – at least in our part of the cosmos – overwhelmingly dominant particles of matter. A contribution from annihilation reactions of dark matter particles, which may be their own antiparticles, is possible, but of unclear significance because of the still quite large uncertainties in the calculation of conventional contributions [18].

On the other hand, the lightest antiparticles, positrons e^+, have long been suspected to partially come from unidentified sources, already since the results of the PAMELA space spectrometer. Figure 6 shows the spectrum of positrons that AMS-02 has measured to date. For better visibility of its structure, the particle flux is multiplied by a factor E^3. There is a low-energy component which is compatible with conventional diffusion sources.

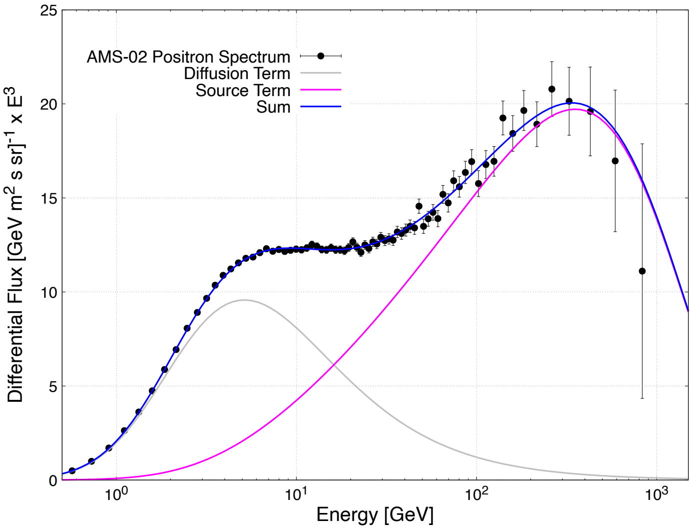


Figure 6: AMS-02 measurement of the differential flux of positrons as a function of the energy E, scaled with $E^{3.0}$ [7]. Error bars represent the total statistical and systematic errors. The diffusion term corresponds to a secondary production of positrons through the interaction of cosmic rays with interstellar matter. The source term corresponds to primary production by a new, not yet identified source.

In addition, at high energies there is a component that can be heuristically described by a source term with a harder spectrum and an exponential cut-off. An example of such a phenomenon would be the annihilation of dark matter particles into electron-positron pairs. In fact, the electron spectrum also allows a similar contribution, but does not require it. One finds a cut-off energy for positrons of $(810^{+310}_{-180})\,\mathrm{GeV}$; in a pair-annihilation reaction this would correspond to the mass of the primary particles.

However, electromagnetic processes can also generate electron-positron pairs. An astrophysical example would be the rapidly changing magnetic fields of pulsars. These are rotating neutron stars whose rotational axis does not coincide with the direction of the magnetic axis. This leads to strong fields in some regions, which can be suitable for generating high-energy positrons. Since positrons easily disappear in interaction with interstellar matter, such point sources should not be located too far from the solar system. Positrons of 100 GeV can e.g. only come from sources some ten thousand years old and located no farther than about one kiloparsec ($\simeq 3 \times 10^{16}$ km) from us [16]. One could therefore expect a slight anisotropy of their directions of incidence, which is not observed with upper limits at the percent level. How far propagation effects would wash out an anisotropy is unclear. This again points out how important it is to better understand diffusive propagation effects.

The search for heavier antinuclei, like antideuterium or antihelium, is particularly fascinating. They are extremely difficult to produce through interactions between matter particles; the probability to form them decreases by orders of magnitude with each additional antinucleon [19]. There are, however, a good handful of antihelium candidates in the AMS-02 data among 176 billion cosmic particles. Sam

Ting presented some of them in a 2018 CERN seminar [20]. The rate is roughly equivalent to one $\overline{\text{He}}$ per year, or one per 100 million He nuclei. On the one hand, this is a very small rate; the systematic significance is difficult to assess because, in particular, the expected background has to be quantified. The fact that this has not happened so far, and that there is no publication, is probably also due to the tiny rate. To ensure that there is no detector malfunction at the level of 1 in 100 million, one needs to know more about the properties of these rare events. Thus the AMS-02 collaboration does not (yet?) claim to have discovered complex cosmic antinuclei.

On the other hand, if at least some of these candidates are taken seriously, there are too many to explain them by conventional nuclear astrophysics. Thus there should be a small, ready-made supply of antimatter somewhere in the galaxy which might have been left over from the Big Bang. That motivated a new search for anti-stars in the Milky Way, i.e. stars made of antimatter. In the catalog of the Fermi satellite there are 14 objects whose photon spectra are compatible with antimatter [21], about 2.5 candidates per million normal stars at a distance between a few 10^{14} and 10^{16} km. They could be considered as sources of $\overline{\text{He}}$ if one knew the release and acceleration mechanism. According to the authors, however, it is more likely that they are normal γ-ray emitters such as pulsars or black holes.

5 Future Projects

It is not clear whether the question of the existence of cosmic antimatter – or of particles originating from dark matter – can be conclusively answered with AMS-02 alone. For the foreseeable future, it will be the only magnetic spectrometer in space, i.e. the only detector that can differentiate between matter and antimatter. Colleagues from Germany [22] and Italy [23] have therefore submitted outlines for follow-up projects in connection with the ESA program “Voyage 2050”. In a nearer future, the HERD project [24] of the Chinese Space Agency – also with participation of WiZARD and AMS members – plans to install a large calorimetric detector on the Chinese space station Tianhe, which is currently under construction. It will allow to look into the spectra of electrons and positrons lumped together. The coming decades will remain exciting.

Acknowledgement

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Martin Pohl, former chair of the SPS TASK section, is professor emeritus of University of Geneva, where he has been director of the "Département de physique nucléaire et corpusculaire" and head of the physics department. After obtaining his PhD at RWTH Aachen in neutrino physics, he participated in collider experiments at DESY and CERN. Since 1998 he works on particle astrophysics experiments.
Besides AMS, his projects include the polarimeter POLAR for hard X-rays on the Chinese space-lab Tiangong 2. He is the main author of two online courses on introductory particle physics on Coursera. In 2020, he published the book “Particles, Fields, Space-Time: From Thomson’s Electron to Higgs’ Boson” (CRC Press, 2020).

Progress in Physics (85)

Magnetic vortices: into the third dimension

Claire Donnelly [1,2], Konstantin L. Metlov [3,4], Valerio Scagnoli [5,6], Manuel Guizar-Sicairos [6], Mirko Holler [6],
Nicholas S. Bingham [5,6], Jörg Raabe [6], Laura J. Heyderman [5,6], Nigel R. Cooper [1], Sebastian Gliga [6]
[1] Cavendish Laboratory, University of Cambridge, JJ Thomson Ave, Cambridge, CB3 0HE, UK
[2] Max Planck Institute for Chemical Physics of Solids, DE-01187 Dresden
[3] Donetsk Institute for Physics and Technology, R. Luxembourg str. 72, UA-83114 Donetsk
[4] Institute for Numerical Mathematics RAS, 8 Gubkina str., RU-119991 Moscow GSP-1
[5] Laboratory for Mesoscopic Systems, Department of Materials, ETH Zürich, CH-8093 Zürich
[6] Paul Scherrer Institute, CH-5232 Villigen PSI

Vortices are familiar phenomena in fluids and gases, apparent for example in tornadoes, hurricanes and whirlpools. Vortices also exist in ferromagnets, where they are characterized by a circulating in-plane magnetization structure. At their center, the magnetization lifts out of the circulation plane, forming a stable and narrow core, a few nanometers in radius (Figure 1a). The resulting pattern leads to flux closure, which reduces stray fields, thereby producing an energetically favorable state. Consequently, vortices form naturally and can exist as parts of larger structures, such as domain walls, or as isolated magnetic states.

Initially discovered within Bloch domain walls in bulk ferromagnets, vortex structures were called 'Bloch lines' [1]. Later, it was predicted that vortices should form the ground state of small magnetic cylinders [2] and possess a very narrow core [3]. The experimental study of isolated vortices in magnetic nanostructures became possible in the early 2000s thanks to advances in lithographic techniques and thin-film deposition, combined with the advent of high lateral resolution magnetic imaging techniques. The first observation of the vortex core was performed using magnetic force microscopy, by exploiting the dipolar interaction between the core and a sharp ferromagnetic tip [4] (Figure 1b). Later, the use of spin-polarized scanning tunneling microscopy, which measures the spin-dependent tunneling current between a magnetic tip and the sample through a vacuum gap, allowed the precise determination of the core structure on the nanoscale [5] (Figure 1c). Vortex formation, along with the size of the core, are defined by the competition between the exchange and magnetostatic interactions [6]. As a result, when vortices form in magnetic nanostructures, they display remarkable stability down to very small nanostructure sizes.

The small size of the core, combined with the stability of vortices, naturally makes these promising candidates for technological applications. However, magnetic devices that range from nonvolatile memories to spintronic systems [7, 8], have long avoided vortices. Indeed, most applications of magnetism in reduced lateral dimensions involve the coherent reversal of the magnetization. This is because the magnetic switching in granular thin film media found in hard drives, or the reversal of the magnetization orientation in nanomagnets, which are part of various magnetoresistive random access memory (MRAM) architectures [9] or of proposed patterned storage media [10], require reliable and fast operation. In this context, the nucleation of vortices is undesirable given that it is not easily reproducible due to material defects and imperfections. This is known as Brown's paradox [11]. Nanomagnets are thus generally engineered through their shape and size to exhibit single-domain behavior, thereby avoiding the vortex state that would otherwise naturally form. Only Arrott's hysteron [12] used a vortex to drive the reversal of the magnetization in an MRAM cell at low switching fields.

The attitude towards vortices has, however, dramatically changed over the past decade and a half. While it was known since the 1970s that vortices possess rich dynamics derived from their topology [13, 14], experiments on vortex dynamics performed using scanning X-ray transmission microscopy, where the magnetic state is probed using circular-

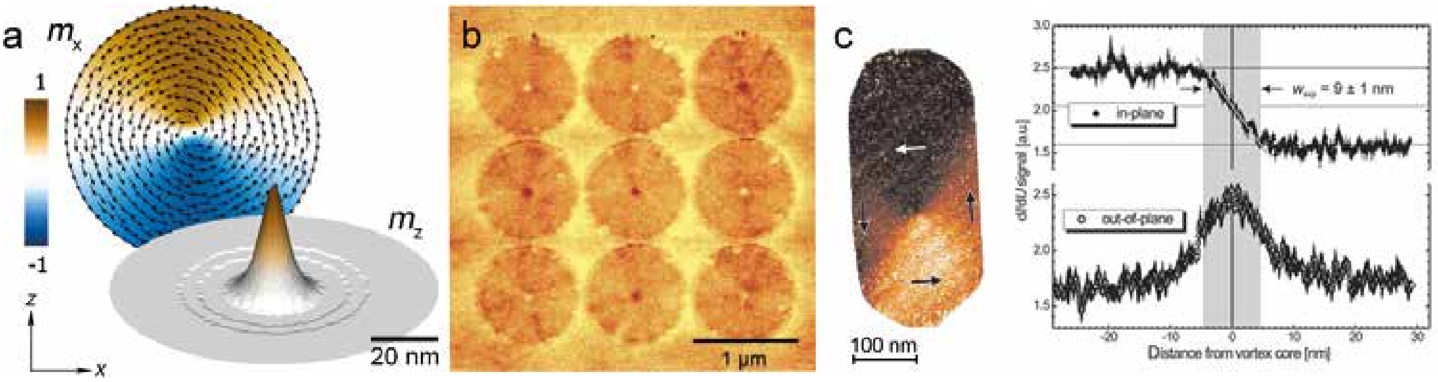

Figure 1. a) Simulated in-plane and out-of-plane magnetic structures of a thin film vortex in a disk-shaped sample 100 nm in radius. The arrows indicate the circulation of the in-plane magnetization. The colormap represents one of the in-plane components (m_x) of the magnetization. The topography of the out-of-plane component of the magnetization (m_z) reveals the structure of the core. b) Experimental observation of the vortex core in circular micron-sized Permalloy disks using magnetic force microscopy. The dark and light spots at the center of the disks indicate the orientation of the core, where the dark spots are cores with magnetization oriented towards the viewer. From Ref. [4]. Reprinted with permission from AAAS. c) Left: measured vortex structure in a ca. 10 nm thick Fe nanoisland with spin-polarized scanning tunneling microscopy. Right: Line sections across the vortex core, showing the in-plane (top) and out-of-plane magnetization components (bottom). From Ref. [5]. Reprinted with permission from AAAS.

ly polarized photons [15], demonstrated that the orientation of the vortex core can easily be reversed using bursts of a low in-plane alternating field [16]. The strength of these bursts was of the order of only a thousandth of a Tesla – a remarkable result in view of the very high stability of the core, which is conferred by the exchange field. (In comparison, the magnitude of the exchange field is of the order of 100 Tesla). Shortly thereafter, it was also found that the vortex core orientation can be reversed using electric currents [17]. There were now means of easily switching between two stable core configurations, an essential requirement for technological applications. Moreover, it was demonstrated that the vortex core reversal unfolds within only a few tens of picoseconds [18, 19], representing one of the fastest known magnetization reversal mechanisms. Following these discoveries, it was clear that the stability and controllable dynamics of vortices makes them suitable for applications such as data storage [20, 21], processing [22, 23] and tunable radio frequency antenna technologies [24 - 26]. Recently, vortices have also been employed in novel approaches to neuromorphic computing [27, 28], based on their tunable resonant frequency, which can even be exploited to produce chaotic oscillations [29, 30], as well as based on the possibility of synchronizing multiple vortex oscillators [31, 32]. Going forward, it is possible that exploring vortices in curved geometries may lead to novel applications based on magnetochiral effects, which have recently been predicted [33 - 35].

The two-dimensional confinement of vortices in thin films has enabled their study in controlled geometries, where thickness plays very little role as far as the vortex profile is concerned. In contrast, in significantly thicker films and bulk samples, vortices evolve into more complex objects. For example, in films about 100 nm thick, the vortex core stretches, resulting in an asymmetric structure [36, 37]. In bulk ferromagnets, it was long known that Bloch lines can assume complex configurations coupled to the three-dimensional structure of Bloch walls. These include twisting and narrowing where the Bloch lines intersect surfaces as well as the formation of micromagnetic singularities, or Bloch points, when the vortex circulation reverses [38]. However, this knowledge was derived from observing surface magnetic states that, combined with analytical models, allowed bulk domain structures in thin perfect crystals to be inferred. The direct observation of nanoscale magnetic features in the bulk of a magnet was not possible.

Recently, the development of X-ray based magnetic nanotomography with a spatial resolution of 100 nm [39] has enabled non-destructive imaging of bulk magnetic structures, opening the possibility to revisit old predictions and to make unexpected observations (see 'X-ray magnetic tomography' box). Among the first observed structures were a pair of magnetic singularities [39]. Bloch points were predicted over 60 years ago and their role in magnetization dynamics is generally well understood [40 - 42, 52, 53]. While the singularities cannot be directly observed, their existence is revealed by the surrounding magnetization state.

The bulk magnetic structure turned out to be very rich in features: upon further analysis of the data in Ref. [39] and based on subsequent measurements, we have established the presence of vortex loops, a few hundreds of nanometers in diameter [43] (Figure 2a). Cross-sections across these loops show that they are composed of bound vortex-antivortex pairs (see 'Topology' box). Moreover, these loops correspond to magnetic vorticity rings that are formally analogous to hydrodynamic vortex rings in fluids [44, 45]. The tomographic reconstruction of one such loop is given in Figure 2b. While the loops we observed have a ring-like structure, their similarity to hydrodynamic vortex rings has a twist. Based on the magnetization distribution, the cross-section of a magnetic vortex ring contains a vortex and an antivortex, while the cross-section of the velocity field of a hydrodynamic vortex ring contains two vortices. This difference is due to the fact that the magnetization is not the magnetic counterpart of hydrodynamic velocity. The common ground for the description of the vortex rings is a different quantity – the vorticity vector. In hydrodynamics it is defined as the rotor of a velocity field. Its magnetic analog can be (albeit in a more complex form) expressed via the rotor of the analogous field obtained from the gradients of the magnetization [44]. Once constructed in this way, the magnetic vorticity vector circulates in a closed loop along the magnetic vortex ring (Figure 2c), just like hydrodynamic vorticity circulates in closed loop around the hydrodynamic vortex ring.

While such magnetic vorticity loops had been predicted to exist in exchange ferromagnets [44], they were expected to be transient structures. In our measurements, we not only established their existence, but also discovered the surprising fact that

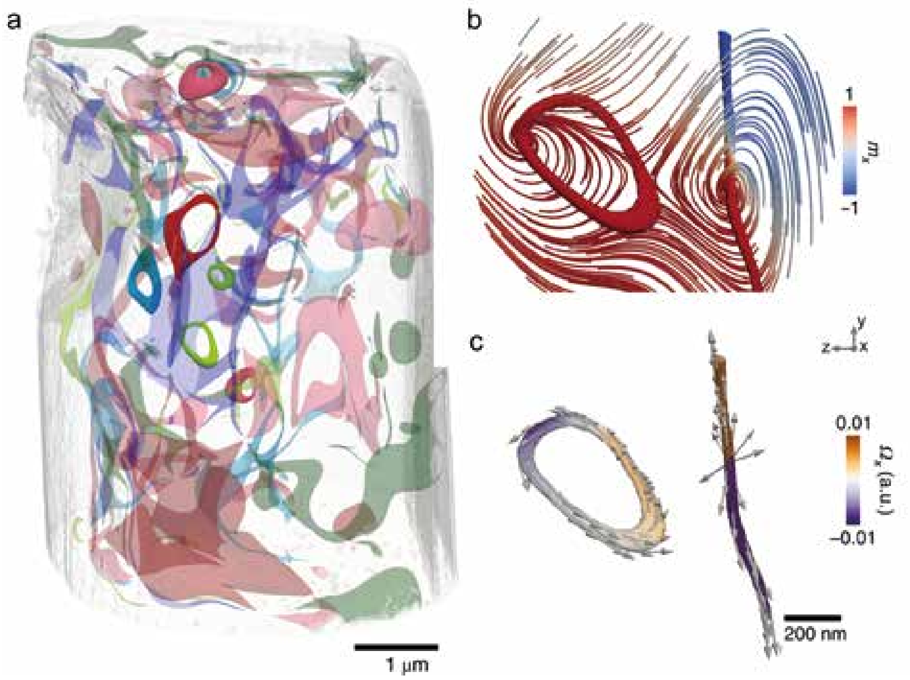

Figure 2. a) A large number of vortex rings are identified within a $GdCo_2$ micropillar. The rings are visualized by isosurfaces representing a defined magnetization direction. b) The cross-section of a ring is composed of a vortex-antivortex pair. The magnetization in the cross-section is represented by streamlines. A vortex structure is observed in the vicinity of the magnetic ring. c) The magnetic vorticity, Ω, represented by the plotted arrows circulates around the ring. Figure reproduced from Ref. [43].

Topology

The magnetization vector has fixed magnitude within a given material and therefore has only two independent components, such that it can be mapped onto a sphere. The problem of finding equilibrium magnetization distributions then consists of continuously mapping one sphere onto another. From topology it is known that all such mappings can be classified by integers. In planar magnetism the topological class of a particular magnetization distribution is known as the skyrmion number or the topological charge. There is no continuous transformation between magnetization distributions with different skyrmion numbers. Such discontinuity implies that the formation of a singularity is required to access a state in which the skyrmion number is modified.

The vortex (Figure 3a) is an example of magnetization distribution with a topological charge of +1. Its counterpart, the antivortex (Figure 3b), has a topological charge of -1. These two objects are thus intimately related and always exist in pairs in infinitely-extended magnets (of which bulk micromagnets are good approximation).

In our measurements, we find a large number of Bloch points (Figure 3c), corresponding to locations where the magnetization reverses its direction within the vortex or the antivortex core. The singularities can equally be classified by their topological charge. The observed magnetic structures around a Bloch point and an anti-Bloch point are shown in Figures 3d,e.

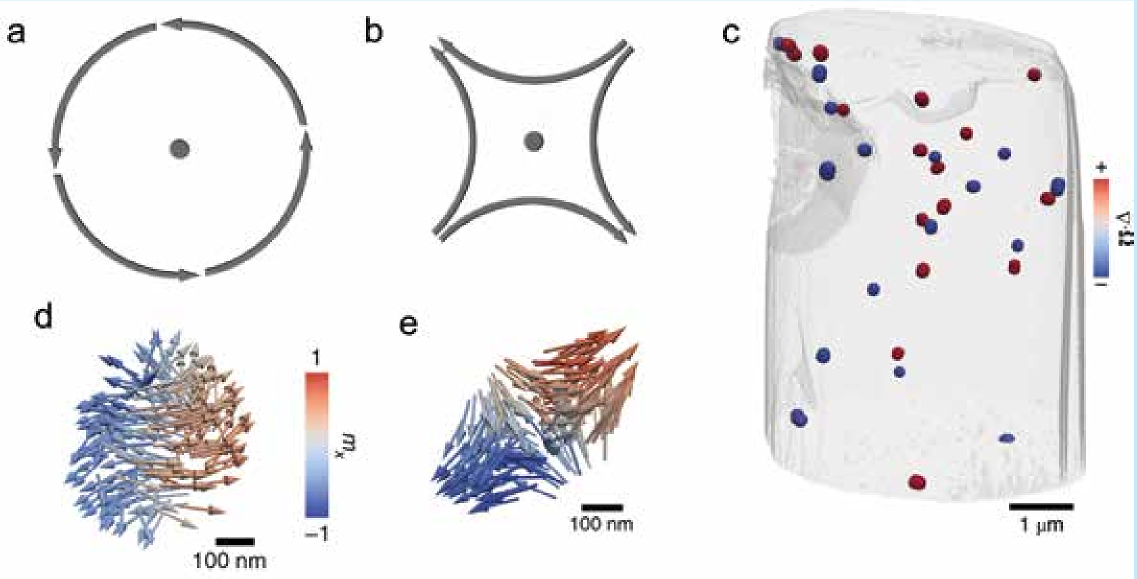

Figure 3. a) Schematic drawing of the in-plane magnetization of a vortex and b) of an antivortex. The central dot represents the core. c) Reconstructed Bloch point locations based on the divergence of the magnetic vorticity. d) Magnetic structure surrounding a Bloch point and e) an anti-Bloch point.

they can form stable, static configurations. Motivated by this finding, we were able to show that their stability is due to the magnetostatic interaction and provided an analytical estimate for the vortex ring size [43, 46]. In addition, we have observed stable vortex loops intersected by magnetic singularities at which the magnetization within the vortex and antivortex cores reverses. These structures have no counterparts in incompressible fluids given that there is no analogue of the local magnetization field in fluid dynamics.

These first observations of magnetic vortex rings represent an exciting step forward for the study of three-dimensional magnetic solitons. Even though the rings are topologically trivial (except when they contain singularities), with the new capabilities of magnetic tomography, it will be possible to unambiguously establish the structure of “knotted” solitons, such as hopfions [44, 47, 48]. Looking back at the history of magnetic vortices, we expect further discoveries, in particular concerning the dynamics of these structures, which may enable novel concepts and applications in information technologies. Recent simulations indicate that exotic structures – charge helices – exist within iron whiskers [49], which have been studied decades ago and were thought to be well understood. Hence, like dolphins who occasionally enjoy gazing at bubble rings, we admire the beauty of magnetic rings and look forward to being surprised for years to come.

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X-ray magnetic tomography

X-ray magnetic tomography involves measuring projections of the magnetic configuration in transmission for many different orientations of the sample with respect to the X-ray propagation direction (Figure 4). In contrast to usual tomography where a scalar quantity is reconstructed, the magnetization is a vector quantity with three components, which need to be determined for each voxel (three-dimensional pixel). The technique is based on the combination of three main aspects: 1) The measurement of high spatial resolution projections of the magnetisation probed with X-ray magnetic circular dichroism [50]; 2) The measurement of these projections for multiple sample orientations – each requiring separate tomographic measurements – in order to probe all components of the magnetisation; 3) The reconstruction of the magnetization with an iterative algorithm based on the angular dependence of the magnetic signal [51].

Once the reconstruction is performed, the next challenge consists of identifying the magnetization structures in three dimensions. To do this effect, the vorticity vector was calculated [43] which allowed determining the nature of topological objects such as vortices and singularities.

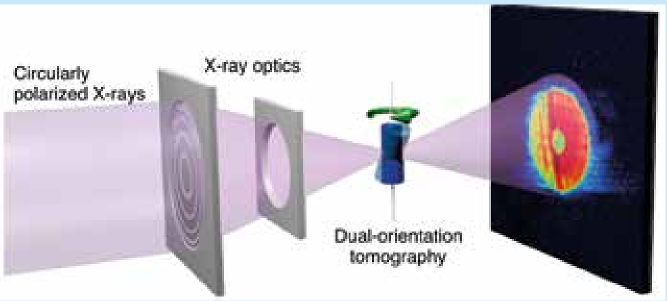

Figure 4. X-ray tomography of a magnetic micropillar. Magnetic projections are measured for two tomographic rotation axes to probe all components of the magnetisation. Figure reproduced from Ref. [43].

Progress in Physics (86)

Intriguing results at the LHCb experiment: the flavour anomalies strengthen

Nicola Serra and Patrick Owen, Physik-Institut, Universität Zürich, CH-8057 Zürich
nicola.serra@cern.ch, powen@physik.uzh.ch

Measurements of decays of B-mesons at the LHCb experiment show an intriguing pattern of deviations with respect to Standard Model predictions. These measurements are consistent with the existence of a new fundamental interaction. The most recent of these measurements has provided the first evidence of lepton universality violation in a single decay, strengthening the New Physics interpretation of these so-called flavour anomalies. Here we discuss the history, status and future prospects of the anomalies.

I. Anomalies in Rare Decays

In 2012 the last particle predicted by the Standard Model of particle physics (SM), the Higgs boson, was discovered by the experiments ATLAS [1] and CMS [2]. Merely 1 year later, in 2013, the first in a series of discrepancies with respect to SM predictions in $b \to s\ell^+\ell^-$ decays appeared in the angular distributions of the $B^0 \to K^{*0}\mu^+\mu^-$ decay [3]. It was immediately suggested that this *anomaly* could be interpreted as a sign of physics beyond the SM [4], often known as New Physics (NP). The $B^0 \to K^*\mu^+\mu^-$ anomaly was subsequently confirmed by other LHCb analyses [5, 6]. These measurements are consistent with the fact that branching ratios of $b \to s\mu^+\mu^-$ transitions are observed to be lower than the SM predictions [7–13].

However, it was pointed out that both the decay rate and angular deviations could be qualitatively explained by a larger-than-expected charm-loop contribution [14, 15]. The so-called charm-loop is a SM process, represented in the Feynman diagram of Fig. 1 (center), for which there is not yet a full consensus on the theory uncertainty. During intense and fruitful discussions on the nature of these discrepancies and the magnitude of the charm-loop contribution, an unexpected new result from LHCb shed a new light on these anomalies. The ratio of branching fraction

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \qquad (1)$$

was measured with 3 fb^{-1} of data by LHCb to be $0.745^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$, deviating by 2.6 standard deviations from the SM prediction [16]. The deviation in R_K is numerically consistent with the low branching fractions in $b \to s\mu^+\mu^-$ processes and with the original anomaly in the angular observables of the $B^0 \to K^*\mu^+\mu^-$ decay. The R_K observable is predicted to be unity in the SM [17–20], due to Lepton Flavour Universality (LFU). LFU is an accidental symmetry of the SM, arising from how the lepton families are organized. LFU breaking cannot be explained by the charm-loop contribution or any other theoretical uncertainty, meaning that deviation from LFU would be a clear sign of NP. The numerical coherence of the anomalies is what makes them particularly interesting and is almost certainly the most compelling hint of NP that has arisen from the Large Hadron Collider (LHC) to date. The only way to understand the correlation between the various observables is to use the language of the effective Lagrangian, where the short-distance four-lepton interaction is encapsulated in so-called Wilson coefficients. This approach is analogous to Fermi's theory of beta decays [21], and allows to consider each observable in rare B-meson decays as a different measurement of the same $b \to s\ell^+\ell^-$ (where ℓ = e, μ) short-distance interaction. Since the same Wilson coefficients appear in different decays, we can combine various channels using this Effective Field Theory (EFT) approach, and also check the consistency between the value of Wilson coefficients measured in different processes. All these rare decays anomalies can be explained by the same numerical shift to the Wilson coefficients C_9 and C_{10} with respect to their SM values.

Further evidence appeared in 2017 when the ratio R_{K*} between the decays $B \to K^*\mu^+\mu^-$ and $B \to K^*e^+e^-$ was measured in two bins of di-lepton invariant mass squared (q^2), showing discrepancies of 2.1 – 2.5σ in each bin.
These discrepancies were in the same direction as the existing rare decay anomalies, suggesting a deficit of muons with respect to electrons. More recently, in 2019 the measurement of R_K at LHCb was updated with 5 fb^{-1}, finding a value of $0.846^{+0.060+0.016}_{-0.054-0.014}$ [22]. This measurement superseded the previous one performed in 2014 [16], leaving the situation unchanged, as while the total uncertainty decreased, the central value approached the SM. In that scenario, the

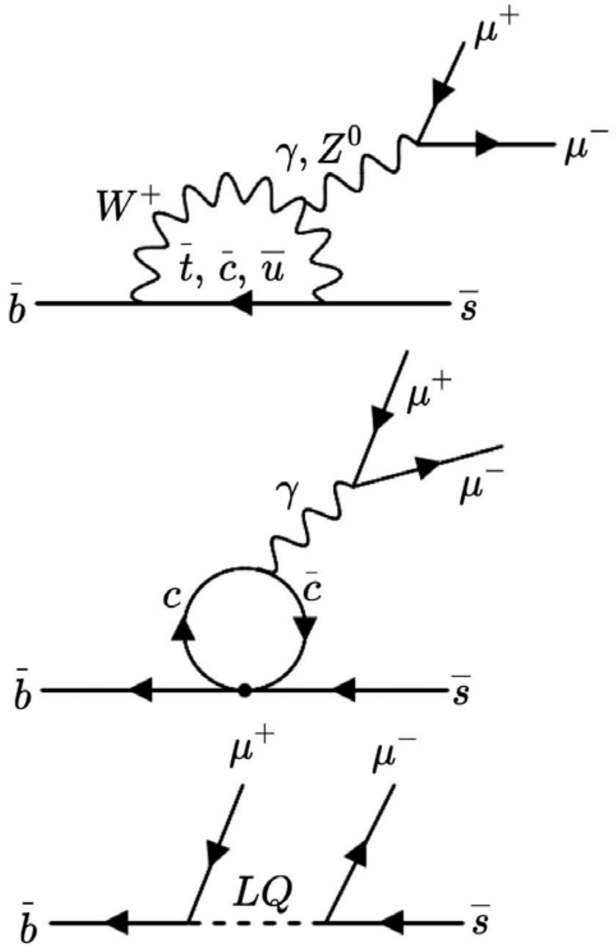

FIG. 1. Possible Feynman diagrams for $b \to s\ell^+\ell^-$ (ℓ = μ, e) processes, for the SM (top), charm-loop (center) and for New Physics mediated by a Leptoquark (bottom).

measurement of R_K with the full Run1&2 data by LHCb was highly anticipated. The new measurement was released in March 2021.

II. The new Measurement

The update of R_K with the entire 9 fb^{-1} of data was made public with a CERN press release, creating a great echo in the mainstream media. The result was $R_K = 0.846^{+0.044}_{-0.041}$ in the region 1.1 GeV^2 < q^2 < 6.0 GeV^2, which corresponds to 3.1σ deviation from SM predictions, consisting of the first evidence for LFU violation in a single B-meson rare decay. The evolution of R_K measurements, is shown in Fig 2. The main control channels for this analysis are the decays $B^+ \to J/\psi(\to \ell^+\ell^-)K^+$ and $B^+ \to \psi(2S)(\to \ell^+\ell^-)K^+$, which have the same experimental signature as the signal, differing only in the value of $q^2 = m_{\ell^+\ell^-}$, corresponding to the mass squared of the J/ψ (~ 9.6 GeV^2) and of the ψ(2S) (~ 13.6 GeV^2), respectively. In order to reduce systematic uncertainties due to imperfect knowledge of the electron and muon efficiencies, the double ratio between $B^+ \to K^+\ell\ell$ and $B^+ \to J/\psi K^+$ defined as

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}\frac{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \qquad (2)$$

is used. In addition, LFU tests of the control channels are used to cross-check the measurement. Notably, the measurement of the LFU single ratio $r(J/\psi)$ = 0.981 ± 0.020 and of the LFU double ratio (with respect to the J/ψ mode) $R(\psi$ (2S)) = 0.997 ± 0.011 give strong confidence in the modeling of muon and electron reconstruction at LHCb.

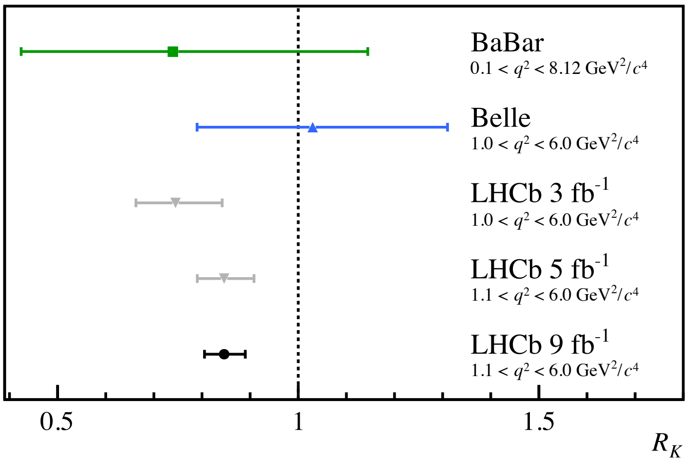

FIG. 2. Evolution of the measurement of R_K [23].

III. The Semileptonic Anomalies

In addition to the rare decays anomalies described in the previous sections, other deviations from SM predictions have been measured in semileptonic decays of B-mesons by the experiments BaBar [24, 25], Belle [26–29] and LHCb [30–32]. These semileptonic anomalies suffer from a large amount of background due to the presence of weakly interacting neutrinos in the final state. However, the coherence between experiments in vastly different environments provides confidence in the results. The analyses measure the LFU ratios, $R(D)$ and $R(D^*)$, defined as the decay probability of the decay $B \to D^{(*)}\tau\nu$ with respect to the lighter-lepton counterpart $B \to D^{(*)}\ell\nu_\ell$, where ℓ denotes either a muon or electron. The global significance of these LFU semileptonic tests is about 3σ [33] from SM predictions.

While the rare decays and semileptonic anomalies cannot be linked model-independently, both can be interpreted as a new fundamental interaction that violates LFU by hierarchically coupling to the lepton and quark generations. The presence of third generation leptons in the semileptonic decays can explain the larger effect with respect to the rare decays anomalies. This fact has led theorists to propose NP models that naturally explain both sets of anomalies simultaneously (see for instance Refs [34–43]). Many of these models predict the existence of Leptoquarks, depicted in the bottom of Fig. 1, which are particles carrying both lepton and baryon numbers. As was pointed out in Refs [34, 36, 44], the semileptonic anomaly would indicate a NP scale of a few TeV, which would have experimental signatures that would be detected directly at the High-luminosity LHC. If all flavour anomalies persist, then, we will probably observe new particles at the ATLAS and CMS upgrades and certainly at the Future Circular Collider (FCC) [45]. Such a discovery could lead to answer some of the fundamental questions in particle physics. For example, the anomalies might be related to the problem of the origin of the masses [46], i.e. the lack of explanation for the very different values of the masses of the different generations of particles.

IV. Future Prospects

The rare decays anomalies are particularly interesting because they consist of several measurements involving $b \to s\ell^+\ell^-$ processes that can be related using an EFT approach. While there is no single measurement yet that deviates more than 5σ from the SM, which is considered the gold standard in particle physics to claim a discovery, several theory groups have combined these measurements by means of fitting Wilson coefficients, obtaining significances greater than 5σ [37, 47–50]. In Ref. [51] it was shown that even adopting an hyper-conservative theory and a conservative statistical approach, a global significance of about 4σ for NP is obtained in rare B-meson decays. The LHCb collaboration has not yet analyzed the full Run1&2 datasets for all related measurements. In particular, the measurement of R_{K*} has only been performed with Run1 data, which is around 25% of the total dataset. The update of this measurement is crucial to increase our confidence in the anomalies. Especially interesting will be the value of R_{K*} in the low-q^2 bin, which is expected to become more compatible with unity due to the large contribution of the photon diagram, depicted in Fig. 1 (top), in this region. Moreover it will be important to measure as precisely as possible all LFU R ratios. For instance, the measurement of $R_{pK} = \frac{\mathcal{B}(\Lambda_b \to pK\mu^+\mu^-)}{\mathcal{B}(\Lambda_b \to pKe^+e^-)}$ [22] has still large uncertainty, but it is consistent with the anomalies. Other LFU R ratios that may have good experimental sensitivities are $R_{K\pi\pi} = \frac{\mathcal{B}(B \to K\pi\pi\mu^+\mu^-)}{\mathcal{B}(B \to K\pi\pi e^+e^-)}$ and $R_{K\pi} = \frac{\mathcal{B}(B \to K\pi\mu^+\mu^-)}{\mathcal{B}(B \to K\pi e^+e^-)}$, where Kπ refers to the region above the K*^{0}(892) resonance.

In addition, measurements of LFU ratios of angular observables in $B^0 \to K^{*0}\ell^+\ell^-$ decays, such as Q_5 [52], will add a fundamental piece to the flavour anomaly puzzle, also allowing discrimination between NP models.

Regarding the semileptonic anomalies, the LHCb measurement of $R(D^*)$ are performed only with Run1 data. Updates of these measurements with Run2 will have a significant increase in precision. In addition, more measurements of the non-excited state, i.e. $R(D)$, are important to clarify the anomalies. The current value of these observables favours a NP explanation consisting of a purely left-handed current, which is consistent with the best fit of the rare decays anomalies, thus suggesting a direct connection between the two sets of anomalies. The measurement of $R(\Lambda_c)$ with the decays $\Lambda_b \to \Lambda_c \tau \nu$ and $\Lambda_b \to \Lambda_c \mu \nu$ could not only increase the significance of the anomalies, but can also be related model-independently to $R(D)$ and $R(D^*)$ [53], providing an important consistency check of these measurements.

Most models explaining the anomalies predict the existence of SM forbidden decays that violate lepton flavour, such as $\tau \to 3\mu$ and $\mu \to 3e$ [54]. These decays could be observed in the near future. Therefore, searches for lepton flavour violating decays of taus at Belle II and LHCb Upgrades, and of muons at dedicated experiments such as Mu3e [55], are of paramount importance.

V. Conclusions

In summary, several flavour anomalies manifesting in rare and semileptonic decays of B-mesons show an interesting pattern that is consistent with the existence of a new fundamental force that couples hierarchically to the three families of quarks and leptons. Analyses with LHCb Run2 data have the potential to clarify whether the anomalies are a genuine sign of physics beyond the SM. In addition, independent measurements of semileptonic anomalies by Belle II and CMS can be expected in the near future.

The unambiguous confirmation of the flavour anomalies would mark the beginning of a new era of discoveries in particle physics. The current and planned upgrades of the LHCb experiment would eventually shed light on the structure and coupling of NP. The possible connection between the anomalies and the violation of lepton flavour, places urgency on experiments such as Mu3e at PSI, which could test some crucial predictions of the most promising NP models explaining the anomalies. Finally, the direct detection of NP particles associated with the flavour anomalies could be possible at ATLAS and CMS or at future experiments at the FCC.

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Milestones in Physics (24)

Development of Laser-based Diagnostics for Magnetic-confinement Devices at CRPP Lausanne (1960s - 1990s)

Antoine Pochelon, on behalf of former members of the Laser Group: Roland Behn, Michael Green, Ivar Kjelberg, Peter Krug, Philip Morgan, Tatsuo Okada, Armando Salito, Mark Siegrist, Reich Watterson and Henri Weisen.

Introduction

This communication presents an account of the use and development of lasers at CRPP, over the years roughly between 1966 and 1996. They were core elements in diagnostic systems to measure basic plasma parameters in magnetic-confinement devices, used for research into controlled thermonuclear fusion. Here, the term plasma describes a fully-ionised gas, frequently hydrogen or its isotopes, which is heated to temperatures of 10^6 K, or higher. Basic heating and containment are achieved by means of a powerful electric current induced in the plasma by the use of external magnetic coils. Besides heating the plasma by the Joule effect, the plasma current generates a magnetic field with field lines perpendicular to a static field produced by a different set of external coils. Together, these two fields create a set of nested closed magnetic flux surfaces on which the plasma electrons and ions are confined due to their relatively narrow Larmor radii, isolating them from material surfaces. For the sake of compactness, further definitions and more-detailed information are presented in the glossary.

The first laser diagnostic at CRPP was deployed in 1966, on a linear device with rotating magnetic fields. The diagnostic measured the electron density by interferometry, using a He-Ne laser as source [A. Heym 1967, A. Berney et al. 1971]. Later, a diagnostic system was developed to determine electron temperature and density in the device, by means of incoherent Thomson scattering from a pulsed ruby laser beam [Z. A. Pietrzyk et al. 1974]. Both systems operated at visible wavelengths.

By 1972 the need to use lasers operating at infrared wavelengths was apparent. This was to increase the sensitivity of interferometric measurements and to attempt ion temperature measurements by coherent Thomson scattering [P. Oettinger 1972]. The fusion community was by now turning its attention to toroidal devices. In particular, the tokamak [M. J. Forrest et al. 1970, J. Wesson 2011] showed excellent performance and became the research machine of choice. Due to its combination of relatively low density and very high temperature, the need for infrared and far-infrared lasers became all the more important. In the early 1970s, as a consequence of the CRPP embarking on a project to build its own tokamak, the centre began developing and constructing CO_2 lasers for diagnostic purposes. Further details are presented later, in the section "Coherent Scattering".

In 1976, building on this experience with lasers, the director, E. S. Weibel, formally created a laser group. Its mission was to provide basic laser diagnostics for the in-house TCA tokamak and to undertake research into, and development of, novel laser-based diagnostics for tokamak plasmas in general. Over the years of its existence, the group embraced many nationalities: American, Australian, Austrian, British, Chinese, German, Italian, Japanese, Luxembourger, Norwegian and Swiss – as well as a guest researcher from Kazakhstan.

The remainder of this article gives an account of the research and development at CRPP devoted to laser diagnostics for tokamak plasmas.

Interferometry

Laser interferometry involves splitting the coherent beam into two; one beam passes through the plasma whilst the other traverses a reference path. On recombining the two beams, there is a phase difference which is proportional to the line integral of the electron density along the path through the plasma – see glossary. The phase difference, and hence sensitivity, increases linearly with laser wavelength, but if it is too long refractive effects degrade beam propagation. Consequently, there is an optimal wavelength to be used, dependent on the characteristics of the plasma. Tokamak plasmas, because of their relatively low densities, require a wavelength in the far infra-red (FIR), ~ 10 to 1000 μm.

The interferometer layout of choice is the Mach-Zehnder configuration, Figure 1. In addition to the reference and probe beams, there is a third component which is modulated at a frequency $\Delta\omega_0$ – either mechanically or electronically [D. Véron, 1974]. Before reaching the detectors, both the probe and reference beams are combined with a component of the modulated beam. As a consequence, the detector outputs are not at the laser frequency ω_0, in the region of 10^{12} Hz, but at the beat frequency $\Delta\omega_0$ – which is in the range 1 – 10^3 kHz. The outputs from the detectors are compared, and the phase shift in the probe beam is determined by the time difference Δt between two zero crossings of the oscillating signals.

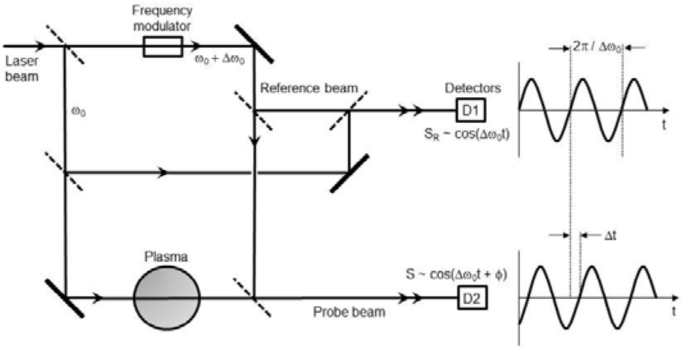

Figure 1 – Schematic of a FIR interferometer

For the TCA tokamak a methyl-iodide laser emitting at 447 μm was used as source. It was optically pumped by a cw CO_2 laser. A rotating cylindrical diffraction grating served as modulator. The interferometer had 8 channels, arranged so that the plasma was probed along 8 parallel paths. They were distributed evenly and were arranged so that the innermost chord passed through the plasma centre while the outermost chord passed close to the edge. Using an Abel-inversion technique, the 8 values of electron line-density were analysed to yield the electron density profile.

The Principles of Thomson Scattering in Plasmas

When a plasma is illuminated by 'light', a number of the incident photons are absorbed by the electrons, which promptly re-emit them [D. E. Evans & J. Katzenstein 1970, D. H. Froula et al. 2011]. Because of their thermal motion, the spectrum of emitted radiation is Doppler broadened – or shifted – with respect to the incident radiation. Due to the large mass ratio between ions and electrons (1836 in the case of protons) the thermal velocity of the latter greatly exceeds that of the former, $\propto \sqrt{m_i/m_e}$ – a factor of 43 at least. Consequently, the direct contribution of ions to the scattering process is negligible although, under certain conditions, their behaviour determines that of the electrons.

For uniform charge distribution, the total power scattered would be almost zero due to interference between contributions of opposite phase. However, the electron density, n_e, fluctuates due to random thermal movements and coherent collective motions, with deviations δn_e. The bunched electrons emit constructively an intensity proportional to $(\delta n_e)^2$. If δn_e is random its magnitude varies as $\sqrt{n_e}$. Hence, the scattered intensity from random electron movements in a plasma is proportional to its density. Scattering from a wave of amplitude δn_e / n_e, would have an intensity proportional to $(\delta n_e)^2$. In a plasma, there is a finite range over which an electric field, caused by a charge imbalance, can exert an influence; electrons flow to restore balance, shielding the field and limiting its range. This characteristic scale length is termed the Debye length, λ_D – see glossary.

Scattering of e.m. radiation from a plasma may be treated as a three-wave interaction. This is illustrated in Figure 2, in terms of wave vectors – where $|\underline{\mathbf{k}}| = 2\pi/\lambda$. An incident wave, of angular frequency ω_0, wavelength λ_0 and wave vector $\underline{\mathbf{k}}_0$, interacts with periodic electron-density fluctuations, characterised by ω_f, λ_f and $\underline{\mathbf{k}}_f$, to produce an e.m. wave of angular frequency ω_s, wavelength λ_s and wave vector $\underline{\mathbf{k}}_s$ at an angle θ to the incident wave. The incident wave is linearly polarised orthogonal to the plane containing the 3 wave vectors.

Momentum conservation requires that $\underline{\mathbf{k}}_s = \underline{\mathbf{k}}_0 + \underline{\mathbf{k}}_f$. As momentum transfer between photons and electrons is negligible, $|\underline{\mathbf{k}}_s| = |\underline{\mathbf{k}}_0|$. It follows that:

$$|\underline{\mathbf{k}}_f| = (4\pi/\lambda_0)\cdot\sin(\theta/2).$$

Thus, by a judicious selection of laser wavelength λ_0 and scattering angle θ, the scale length and propagation direction of the observed plasma-density fluctuations may be chosen. Periodic fluctuations in a direction parallel to $\underline{\mathbf{k}}_f$ and of wavelength $2\pi/|\underline{\mathbf{k}}_f|$ will be preferentially detected.

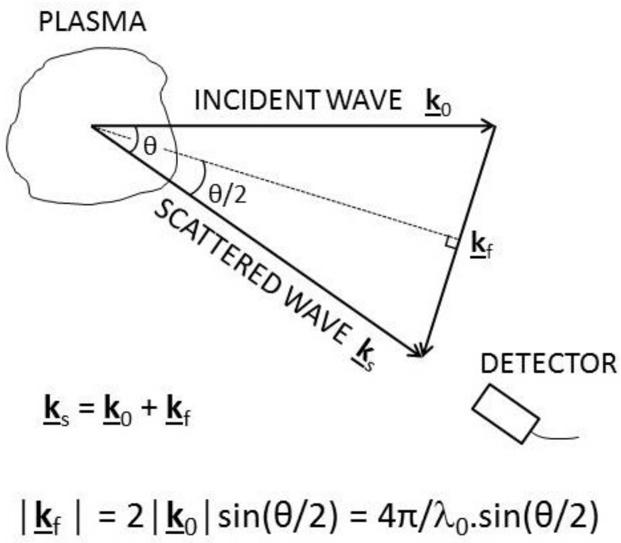

Figure 2 – Vector diagram defining scattering geometry

It is the ratio of the fluctuation wavelength to the plasma Debye length that determines the shape of the spectrum of the scattered light observed. A dimensionless parameter $\alpha = (\underline{\mathbf{k}}_f\,\lambda_D)^{-1}$ is useful in characterising this. For $\alpha << 1$ the scattering is termed incoherent, i.e. it is from uncorrelated, or random, electron density fluctuations. As α approaches 1, coherent, or collective, scattering from correlated fluctuations is observed, whilst incoherent scattering becomes less important. When $\alpha >> 1$, coherent scattering becomes dominant.

The spectral density function $S(\underline{\mathbf{k}}, \omega)$ defines the distribution of scattered power versus frequency for a given $\underline{\mathbf{k}}$. Salpeter introduced an approximation for the function, dividing it into two separate terms for electrons and ions – although the scattering is always by electrons. Thus,

$$S(\underline{\mathbf{k}}, \omega) = S_e(\underline{\mathbf{k}}, \omega) + S_i(\underline{\mathbf{k}}, \omega).$$

The spectral density functions for electrons and ions, as a function of α, are shown in Figures 3 and 4, respectively. They represent frequency shifts from the incident laser frequency ω_0. The functions are plotted utilising the dimensionless frequency variables x_e and x_i.

These are defined in terms of angular frequency, wave vector and thermal velocity, i.e. $x_e = \omega / \underline{\mathbf{k}}v_e$ and $x_i = \omega / \underline{\mathbf{k}}v_i$. If the functions were plotted in terms of frequency the electron term would be at least 43 times broader than the ion term, because of the widely-differing thermal velocities. The spectral density functions are symmetrical about x = 0, but here the values for negative x are omitted. For a discussion of the spectral density function and Salpeter's approximation, the reader is referred to the work of Evans and Katzenstein (1970).

Considering the electron feature in Figure 3, for $\alpha = 0$ the spectrum is a Gaussian with half-width determined by the electron thermal velocity – which is proportional to $\sqrt{T_e}$ – permitting T_e to be determined. As α is increased through 0.5 and 0.75 to 1, the spectrum changes from Gaussian to develop a shoulder away from $x_e = 0$. This is due to correlated effects becoming more important.

Finally, as α is further increased through 2 to 3, the spectrum becomes progressively dominated by coherent scattering and is markedly peaked off axis. This peak is due to coherent scattering from longitudinal electron plasma waves.

If the scattering system is absolutely calibrated, the intensity of the scattered power gives n_e. However, as shown in the glossary, the scattered power is minuscule. This, coupled with the fact that there is strong background emission from the plasma, dictates that a very powerful narrow-band light source is required. Thus, it was not until the advent of pulsed optical lasers of high power that incoherent Thomson scattering became feasible as a diagnostic. Appendix 1 gives a short account of how such a measurement in 1969 changed the course of magnetically-confined fusion research, by demonstrating the superiority of the tokamak to other devices of that era and leading to its position of pre-eminence today.

Turning now to the ion feature in Figure 4, when $\alpha = 0$ the spectrum is devoid of scattered power. Correlated fluctuations are too long-scale to make any contribution. As α increases from zero, through 0.5, 0.75 to 1, the spectrum exhibits progressively-increasing scattered power due to the influence of correlated effects. In particular, scattering occurs from electron 'bunches' Debye-shielding the ions. For $\alpha \approx 1$, the spectrum half-width is largely determined by the ion thermal velocity, $\sqrt{T_i}$, permitting T_i to be determined – as long as T_e and n_e are also known. As α is further increased, the off-axis shoulder of the spectrum continues to grow as cooperative effects dominate. This peak is a manifestation of the ion-acoustic wave, which is very prominent for large values of α and high T_e/T_i ratios.

Applications to the TCA Tokamak

Incoherent Scattering

A diagnostic system was designed and installed on the TCA tokamak, to measure electron temperature. It used a pulsed ruby laser emitting at 694.3 nm. Figure 5 shows a diagrammatic representation of the arrangement.

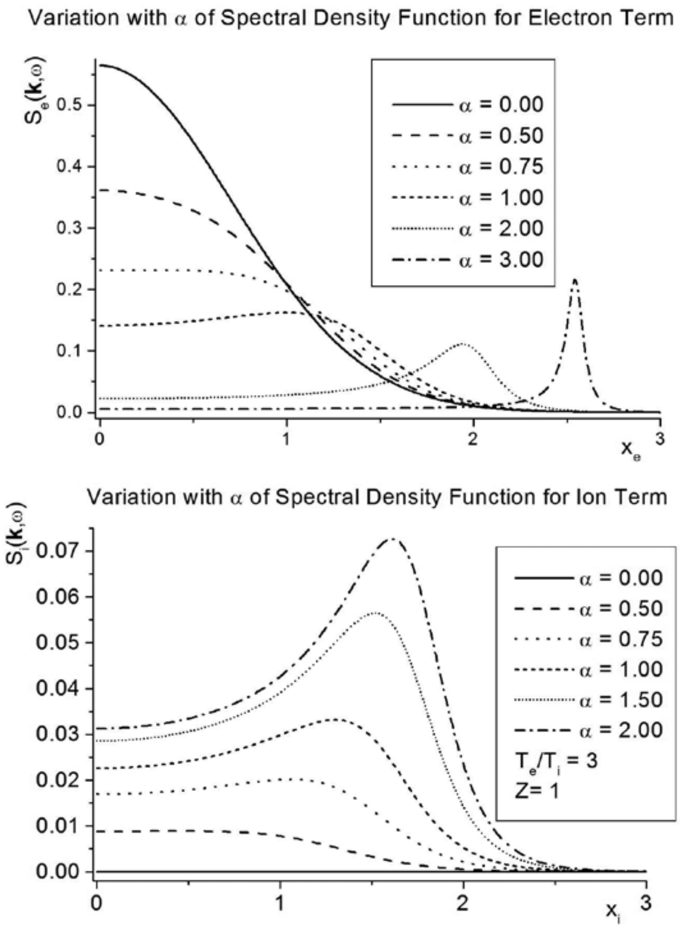

Figure 3 (top) and Figure 4 (bottom)

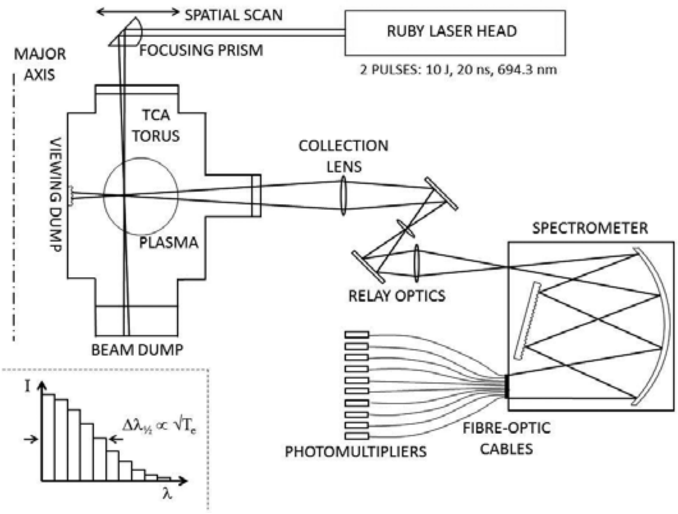

Figure 5 – Layout of Thomson-scattering diagnostic

The laser beam is deflected and focused vertically downwards through a window to a point on the plasma mid plane. Non-scattered light is efficiently absorbed in a beam dump. The electron temperature profile is obtained by scanning, one spatial point per tokamak pulse, across the minor radius on the plasma mid plane – by effectively moving the prism between pulses. The laser head, input prism, collection optics, relay optics and detection system are all mounted on a 2-tier trolley. The trolley is moved by means of a stepping motor drive connected to a rack and pinion, eliminating the need to realign and refocus the optics during a scan.

Light scattered at 90° is collected and relayed to a focus at the entrance slit of a 1-m grating spectrometer. The typical plasma parameters were: $n_e = 5 \times 10^{19}$ m^{-3} and $T_e = 9.3 \times 10^6$ K which, for 90° scattering, gives a value of $\alpha \sim 2.6 \times 10^{-3}$, essentially zero. At the spectrometer exit aperture, the dispersed light falls onto a 10-segment linear fibre-optic image dissector. Each segment collects light from a different wavelength band and is coupled to a photomultiplier by means of an optical-fibre bundle. The laser system provides two separate pulses per tokamak discharge. Inset in Figure 5 is a depiction of how the spectrum of scattered light would be divided among the ten channels. For the parameters given above, $2 \cdot \Delta\lambda_{1/2} = 93$ nm FWHM.

Coherent Scattering

In a tokamak plasma, due to its combination of low density and high temperature, the Debye length is in the range of 10 to 100 μm. Thus, to obtain a value of α around unity, to measure plasma ion temperature, either the observation angle θ has to be extremely small (tenths of a degree) at optical wavelengths or, to employ an angle of several tens of degrees, the laser wavelength has to be in the FIR region. The former approach leads to extremely poor spatial resolution, as scattered light is collected from along a large part of the path of the incident laser beam through the plasma. The latter approach requires an appropriately-powerful laser and an adequately-sensitive detector in this challenging wavelength regime.

It is against this background that the CRPP devoted much effort into developing a pulsed heavy-water vapour (D_2O)

laser operating at 385 μm. The D_2O laser was optically pumped using a multi-stage CO_2 laser system. The TEA (transversely excited atmospheric) CO_2 modules were designed and built in-house, utilising previous knowledge acquired at the Centre. Early work had investigated the characteristics of a system where a 1-m long active section comprised 100 distributed pins as cathode, to achieve ionisation, with a solid rod as anode [P. Oettinger 1972]. Later work concentrated on achieving uniform glow excitation, by using UV pre-ionisation followed by the main discharge, in a configuration employing a flat grid structure as one electrode, through which the UV radiation passed, with the other being a solid Rogowski-profiled electrode [P. Boulanger et al. 1973].

Throughout the various designs, improvements in performance were achieved by careful optimisation of the mixture of the active gases used (CO_2, N_2 and He) and by the judicious use of low-ionisation-potential additives [P. Oettinger 1972, A. Lietti 1978]. Finally, a number of innovations developed elsewhere were incorporated – notably the use of self-synchronising UV pre-ionisation, from side arcs, and the employment of two solid electrodes with a uniform-field Chang profile – to further improve the uniformity and reliability of the laser discharge [M. R. Green et al. 1978].

Initially, the whole pumping chain comprised CO_2 TEA lasers built in house. Figure 6a shows a photograph of the main parts of the system, including the D_2O laser, whilst Figure 6b is a sketch identifying its key elements. The hybrid oscillator employed a TEA section for gain and a low pressure section (~ 20 mbar) for single-mode selection and line-width control.

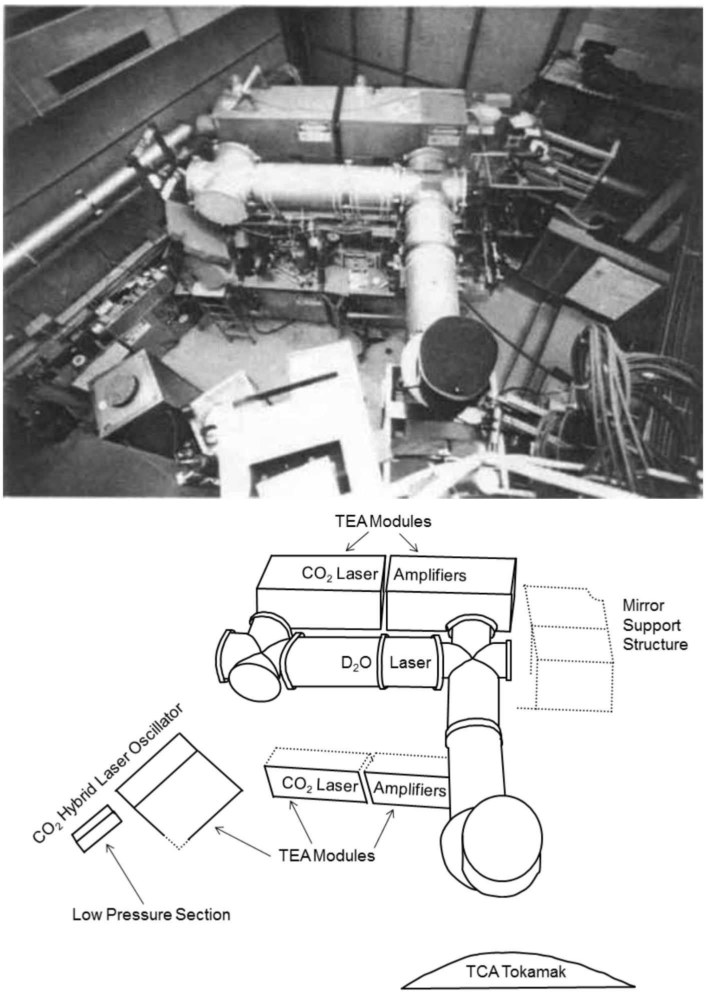

Figure 6 – a: Photograph of initial laser arrangement for T_i measurements on TCA. b: Sketch outlining the key elements.

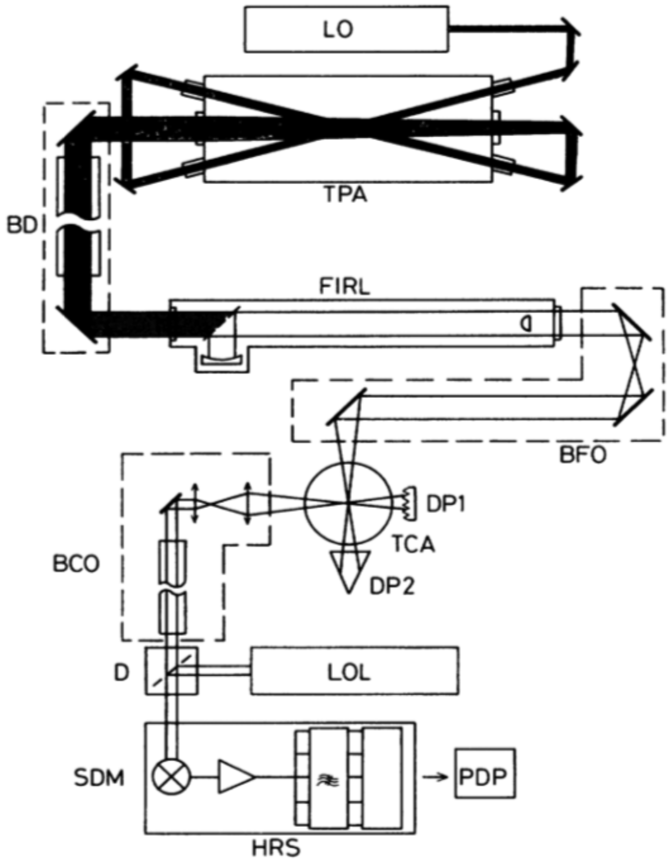

Figure 7 – Layout of coherent-scattering apparatus on TCA. LO: CO_2 hybrid laser oscillator, TPA: triple-pass amplifier, BD: beam duct, FIRL: FIR laser, BFO: beam focusing optics, DP1, DP2: beam dumps, BCO: beam collection optics, D: diplexer, LOL: local oscillator laser, SDM: Schottky diode mixer, HRS: heterodyne receiver system.

Later, a commercial e-beam-excited CO_2 laser, operating at 3 bar, was acquired for use as the final-stage amplifier. The pulses from the hybrid oscillator were fed into it in a triple-pass configuration. Under typical operating conditions the CO_2 laser system delivered 600 J, on the 9R(22) line at 9.26 µm, in a 1.4 microsecond single-mode pulse [R. Behn et al. 1985]. A schematic of the final arrangement of the equipment for scattering measurements on the TCA tokamak is shown in Figure 7. Because of the size of the final-stage CO_2 amplifier, together with the oscillator it was housed in a separate building, and was coupled to the D_2O laser via a 70-m-long beam duct.

The D_2O laser had a 4-m-long unstable resonator in an L shape with a wire grid at the vertex to allow efficient coupling of the pump beam. At a filling pressure of 6.5 mbar the FIR laser produced 0.5 J in 1.4 μs. For detection and spectral analysis of the scattered radiation use was made of a heterodyne receiver with an optically-pumped CD_3Cl (deuterated methyl chloride) FIR laser as local oscillator. Its emission was combined with the scattered radiation in an optical diplexer and mixed in a Schottky-barrier diode. The resulting IF signal, centred around 3.6 GHz, was amplified and split into twelve channels with a bandwidth of 80 MHz each. The signals from the output of the receiver were fed into a CAMAC analogue-to-digital converter which comprised a gated integrator. A fuller description is given in [R. Behn et al. 1989].

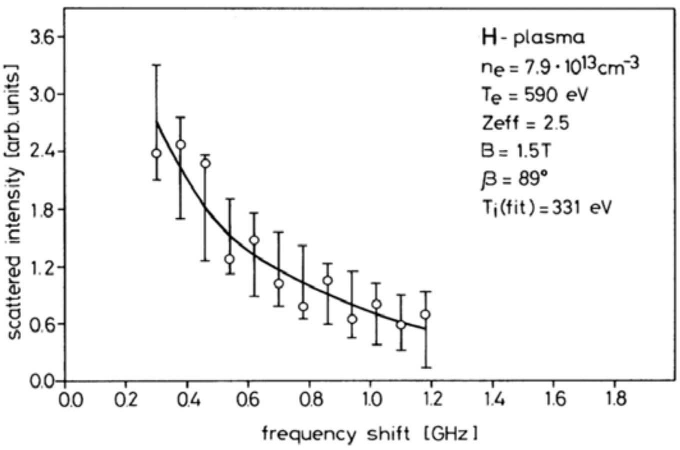

Figure 8 – Best fit to experimental data from scattering from a H plasma in TCA.

The scattering experiments were carried out in TCA plasmas at electron densities greater than 5 × 10^{19} m^{-3}. Under these conditions the signal-to-noise ratio was sufficient to evaluate the ion temperature from data recorded in a single laser shot.

The spectrum of scattered radiation from a hydrogen plasma is presented in Figure 8. The circles represent the measured signals per spectral channel of 80-MHz bandwidth after integration over the 1.4 μs pulse length of the D_2O laser. The solid curve represents the best fit to the data points with the ion temperature and a vertical scaling factor as the two free parameters.

Other plasma parameters required by the fitting routine – such as electron density n_e, electron temperature T_e, and the effective ion charge Z_{eff} – have been introduced as known quantities. The electron density had been measured by interferometry and the electron temperature by ruby-laser scattering. The Z_{eff} values were not precisely known and therefore typical data for TCA discharges have been used. With the introduction of given values for these 3 parameters, an ion temperature of T_i = 331 eV was found with an estimated precision of 20 to 25 %. Comparison with measurements from a neutral-particle analyser showed reasonably good agreement, in particular in deuterium plasmas.

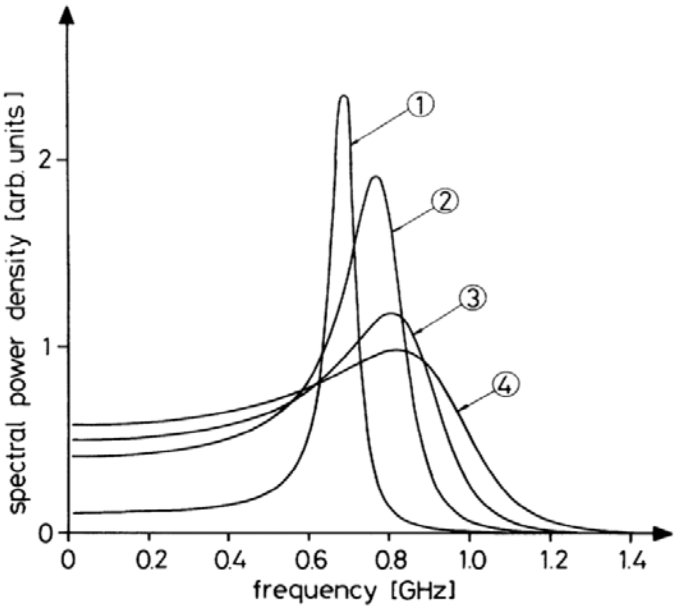

Figure 9 – Calculated spectra for He plasma with T_e = 670 eV and Z_{eff} = 4.4, for various values of T_i. Curves 1 to 4: T_i = 100, 200, 300 and 400 eV. Curve 1 has been reduced vertically by × 3.

For a He plasma, theory predicts that the ion-acoustic resonance should be clearly visible as long as T_e / T_i > 1 (see Figure 9). Figure 10 shows a measured spectrum for a He plasma in TCA recorded in a single laser shot. Good agreement was observed with the predictions of theory, assuming density fluctuations at the thermal level. In the case of a He plasma with given T_e a variation of T_i leads to a significant change in position and half-width of the resonance peak [R. Behn et al. 1989] which allows an unambiguous evaluation of T_i.

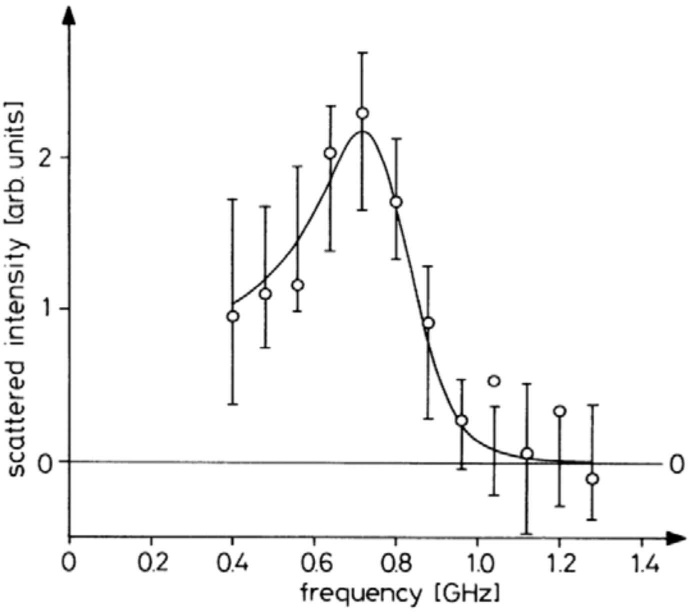

Figure 10 – Best fit to experimental data from scattering from a He plasma in TCA. T_e = 670 eV, Z_{eff} = 4.4, n_e = 7 × 10^{19} m^{-3}, ($\mathbf{k}$·$\mathbf{B}$) = 86°. The fit yields T_i = 250 eV.

Further investigations indicated that the precision could be maintained provided the uncertainties associated with the other plasma parameters, required by the fitting routine (especially T_e), remained below 10 %. At the time the overall precision was mainly limited by the signal-to-noise ratio, which led to the error bars evaluated.

In summary, collective Thomson scattering of FIR laser radiation has been applied to measure the ion temperature of a tokamak plasma. The observed spectra could clearly be identified as collective scattering from thermal density fluctuations. For the first time the ion temperature could be obtained from data recorded in a single laser shot.

However, thereafter, this technique has not been used on another tokamak to measure T_i. This is due to the complexity and size of the apparatus and the availability of simpler methods offering better precision. One of the main drawbacks of the system described is the low efficiency of the optical pumping of the FIR laser, viz. 0.5 J / 600 J = 8.3 × 10^{-4}. If a pulsed high-power FIR laser of similar characteristics could be pumped more efficiently the method might become competitive. The theoretical limit on efficiency, using pumping lasers and FIR lasers in the same wavelength bands as currently described, is of order 10^{-2}, so there is scope for improvement. Spatial profiles could be obtained by using multiple-detection and mixing systems. For the current generation of medium-size tokamaks, with pulse lengths ranging from seconds to several tens of seconds, temporal profiles of T_i will require faster pumping of the FIR laser, i.e. recharging of the CO_2 laser.

The first Phase Contrast Imaging (PCI) diagnostic on a fusion research device

The phase contrast method was first developed for use in microscopy, where it allows the visualisation of transparent specimens that only induce very small phase shifts of the transmitted light. This principle was applied to the detection of density fluctuations by plasma turbulence and by radio-frequency driven waves in the TCA tokamak, the precursor of TCV at CRPP. It used the beam of a low power CO_2 laser, expanded to a width of 23 cm, encompassing most of the TCA plasma diameter [H. Weisen 1988].

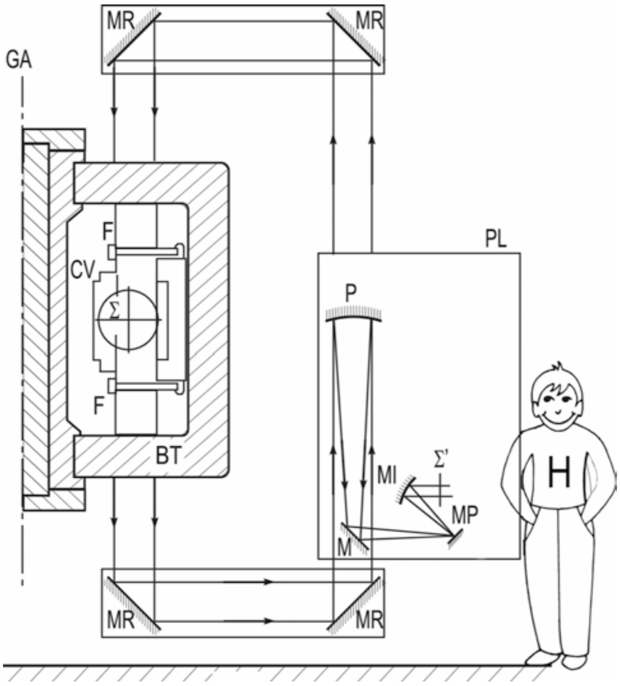

Figure 11 – Detection side of PCI setup on TCA. PL: optical 'breadboard', P: parabolic mirror, M, MR: flat mirrors, MI: imaging mirror, MP: phase mirror, F: vacuum windows made of NaCl, GA: torus axis, CV: TCA vacuum vessel, BT: toroidal field coils, Σ: nominal object plane, Σ' image plane with detectors.
The 8-Watt CO_2 waveguide laser and beam expansion optics were mounted on the opposite side of the 'breadboard'.

Phase shifts caused by the plasma are converted into detectable intensity variations by a phase mirror (MP) which introduces a π/2 phase shift between diffracted light and undiffracted light thanks to a groove a fraction of a mm wide. Its width is matched to that of the focal spot produced by mirror P. By obviating the need for a reference beam, a PCI has a higher sensitivity than an interferometer built with comparable components and using the same laser and detectors. It also benefits from a very high degree of resilience to small movements and vibrations when built for passive stability, as shown in the diagram. The price for this advantage is that the PCI provides a high-pass filtered image, in the spatial sense, of the phase perturbations, i.e. it only reveals fluctuations with wavenumbers above about 2π/D, where D is the width of the beam, i.e. $\underline{\mathbf{k}}_{\perp} > 0.3$ radian / cm.

The device is best remembered for having provided the first observation of mode conversion from a long wavelength radio frequency compressional wave (the fast magnetosonic wave) to a shorter wavelength kinetic wave, the kinetic Alfvén wave (KAW), which propagates inward from a resonance layer in the plasma [H. Weisen et al. 1989]. These were excited in Alfvén wave heating experiments on TCA using in-vessel antennae at frequencies near 2 MHz. An amplitude and phase profile of a KAW are shown in figure 12. The measurement of local Alfvén resonances was put to good use for inferring the local plasma current density in TCA, using the dependence of the resonance condition on the helicity of the magnetic field lines.

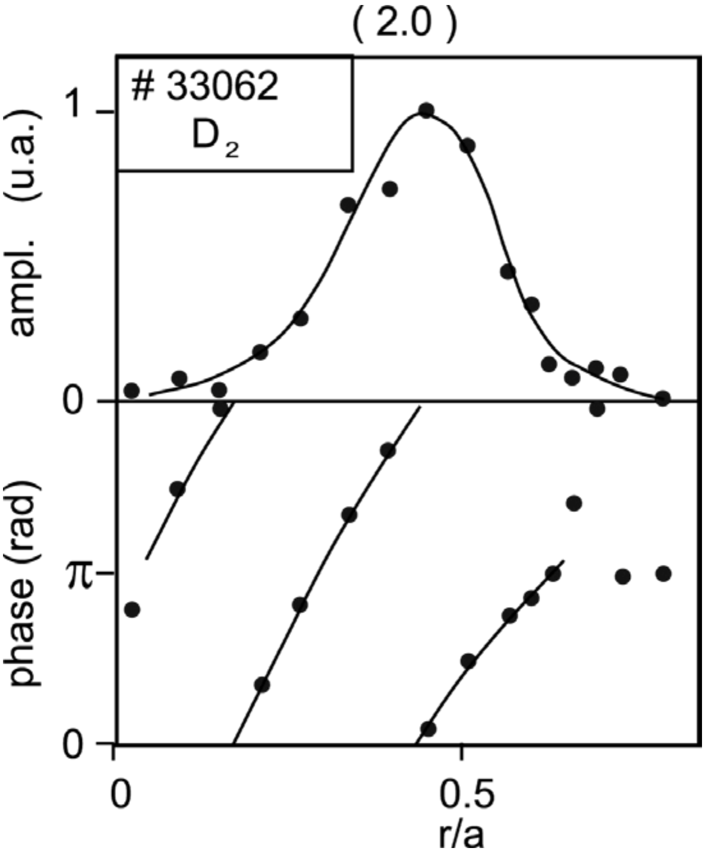

Figure 12 – Amplitude and phase profiles of a mode converted kinetic Alfvén wave with mode numbers n = 2 and m = 0 produced during Alfvén wave heating in TCA. m is the poloidal mode number and n is the toroidal mode number. r/a is the normalised plasma radius.

The Phase Contrast method was subsequently adopted on several fusion research devices, mostly tokamaks, including C-MOD (USA), DIII-D (USA), LHD (Japan) and TCV (Switzerland). These installations often incorporated improvements and the addition of new features, such as heterodyne detection on C-MOD, the provision of resolution along the incident beam direction by making use of the field-line shear in the LHD stellarator, and high spatial resolution in TCV using a toroidal view.

Concluding Remarks

This article presents an account of the development of laser-based diagnostics for magnetic-confinement devices, especially tokamaks, at CRPP Lausanne during the decades 1960s to 1990s. In addition, the use of these diagnostics on the TCA tokamak is described, together with details of the laser development undertaken.

Incoherent Thomson scattering and FIR interferometry were used to measure electron temperature and electron density, respectively. As already-well-established techniques at that time, there was nothing novel about them or their use – particularly as they used commercially-available lasers – although the systems were designed in-house and much of the associated equipment was built there. Nevertheless, they saw a long life as routine diagnostics for measuring T_e and n_e in TCA plasmas, during various experimental campaigns. Also, they provided additional data needed in order to deduce ion temperatures from the coherent Thomson scattering measurements.

These ion temperature measurements were refined to the point where T_i in TCA could be determined in a single laser pulse – a notable first. As already mentioned, the technique has not subsequently been used elsewhere. This arises from its complexity and the availability of alternative simpler methods, e.g. Neutral Particle Analysis and Charge-exchange Recombination Spectroscopy (CXRS) [Wesson 2011].

However, as tokamaks become larger and heavy metals replace low-Z materials in internal regions of high power and particle loading, these techniques will become unreliable. With longer path lengths, the flux of escaping neutral particles from the plasma core will be much reduced due to many more collisions en route to the plasma edge, whilst a reduction of fully-stripped light ions in the core will cause problems for CXRS. Coherent Thomson scattering will be unaffected by these issues, so the technique might enjoy a renaissance – especially as the large tokamaks will operate in quasi-continuous mode; thus a slow laser repetition rate is of little disadvantage.

Finally, Phase Contrast Interferometry has been successfully applied to TCA, the first time the technique had been used to study a magnetically-confined plasma. Its most noteworthy achievement was to demonstrate mode conversion from the fast magneto-sonic wave to the shorter wavelength kinetic Alfvén wave. As noted, this technique has since been successfully implemented on several other fusion research devices worldwide.

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Glossary

Tokamak: Tokamak is an acronym from “toroidal chamber with magnetic coils” in the Russian language.

Interferometry: In a plasma, there is a natural oscillation frequency of the electrons, ω_{pe}, given by

$$\omega_{pe} = (n_e e^2 / m_e \varepsilon_0)^{½},$$

where n_e is the electron density, e is the electronic charge, m_e is the mass of the electron and ε_0 is the permittivity of free space.

For a laser frequency ω_0, such that $\omega_0^2 \gg \omega_{pe}^2$, the plasma refractive index is given by:

$$\mu = [1 - (\omega_{pe}^2 / \omega_0^2)].$$

It can be shown that the phase difference between the reference and probe beam is:

$$\phi = [\lambda_0 e^2 / (4\pi\varepsilon_0 m_e c^2)] \cdot \int n_e dl,$$

where λ_0 is the laser wavelength and c is the velocity of light.

Debye Length: The Debye length, λ_D, defines the range over which a charge imbalance can extend in a plasma; electrons flow to restore balance, shielding the field and limiting its range. Its value is given by:
$\lambda_D = (\varepsilon_0 k T_e / n_e e^2)^{1/2}\, m$, k is Boltzmann’s constant.

Scattered Power: If the scattering system is absolutely calibrated, the intensity of the scattered power gives n_e. The ratio of incident to scattered power is given by:

$$\frac{P_S}{P_0} = n_e \cdot l \cdot d\Omega \cdot r_e^2 S(\boldsymbol{k}, \omega),$$

where l is the length from which scattered radiation is collected, $d\Omega$ is the collection solid angle and r_e is the classical electron radius. Taking values typical of a tokamak: $n_e = 3 \times 10^{19}$ m^{-3}, $l = 0.01$ m, $d\Omega = 5 \times 10^{-3}$ sr and, integrating over all frequencies, $S(\boldsymbol{k},\omega) = 1$. Using these values in the equation, $P_s / P_0 \approx 10^{-14}$.

Electron Volt (eV): This unit is often used as a measure of temperature. 1 eV = 1.16×10^4 K.

Appendix 1: Measurements that Brought the Tokamak into Prominence

In 1969, a team from the UKAEA's Culham Laboratory made measurements on the T3-A tokamak at the Kurchatov Institute in Moscow. Using the technique of incoherent Thomson scattering from a pulsed ruby-laser beam, they succeeded in determining unambiguously the electron temperature of the plasma and confirmed existing density measurements [N. J. Peacock et al. 1969, M. J. Forrest et al. 1970]. The Russians had inferred very good values for the temperature from indirect measurements, which depended on the correctness of a number of assumptions that had to be made. There had been scepticism of the Russian claims in the West, because their results were so much better than anybody else could obtain using a variety of other magnetic-confinement devices.

The Culham team brought their own equipment, much of which they had designed and built. After overcoming several difficulties, they were finally successful and confirmed all that the Russians were claiming. Indeed, it turned out that the Russians had been quite conservative in their claims. One of the difficulties encountered was the high level of light emitted by the T3-A plasma, against which the scattered laser light had to be detected. This background light was caused by a high concentration of heavy-metal impurities in the plasma. Initially, the laser was operated in relaxation mode, producing ~ 100 J of energy in a 1 ms pulse. When the laser was modified to operate in Q-switched mode, it produced a 6 J pulse in 25 ns. This gave an improvement in the S/N ratio by a factor of 2.4×10^3 – sufficient to overcome the background light and to obtain good data.

The results from the scattering measurements had a huge impact on the fusion community, and can be regarded as a turning point in magnetic-confinement research. In laboratories throughout the West, many researchers abandoned their own confinement devices and started building tokamaks – or adapted their devices to a tokamak configuration. Today, the tokamak is the preeminent research device in this branch of fusion, as witnessed by the Joint European Torus (JET) and, looking ahead a few years, the International Thermonuclear Experimental Reactor (ITER).

As an amusing aside, following this successful collaboration between the UK and the USSR, the matter was raised in the House of Lords. It is recorded in *Hansard* that a Peer, congratulating the British team on their achievements in Moscow enquired: “How did the team measure a temperature in excess of 10,000,000 degrees Celsius?” Back came a reply from another Lord: “I suppose, my Lords, that they used a very long thermometer”!

Physicists in Industry (12)

Startups – From great physics to innovative products

Thilo Stöferle

Startup companies are an important innovation engine that transfers knowledge into products. Despite the COVID pandemic, 2020 has been a record-breaking year with respect to the number of companies founded in Switzerland: overall more than 46000. But this is just the continuation of a trend that has been going on for a decade. Especially in physics and the technology sector in general, new directions such as quantum technologies are getting traction and are leading a new wave of startups.

Therefore, at this year's joint annual meeting of the Austrian and Swiss Physical Societies in Innsbruck, the focus of the respective “Physics in Industry” sections was on these young companies that are formed as off-spring from academic research. The jointly organized session covered the full range from newly founded startups with some years ahead before the launch of a first prototype to seasoned spin-offs that have become world leader in their market segment. As the following summaries illustrate, their exciting and very diverse stories were inspiring and give an excellent grasp of what entrepreneurship and innovation means, and how fun and rewarding it can be to initiate or be part of a startup company.

Jens Herbig from **IONICON** kicked off the session, showing vividly how a university spin-off can become market leader for real-time gas analyzers. Setups for proton-transfer reactions and time-of-flight mass spectrometers that once filled whole university labs had to be shrunk into easy-to-use small instruments that today can be used for a wide set of applications ranging from semiconductor industry process monitoring to breath analysis for pharmacokinetics and even a 1-minute COVID test.

A startup in a very early phase was presented by ***Niklas Luhmann*** from **Invisible Light Labs**. He explained how a membrane (MEMS resonator) can change its frequency upon absorption of infrared or THz radiation. This detection method outperforms classical Fourier-transform IR spectroscopy by orders of magnitude in sensitivity and can even detect photon noise. The main challenges for the next years are to build a prototype instrument and go to market successfully.

It is not necessarily the research topic itself but sometimes rather the means to get good research results which can spark a successful start-up. This was impressively demonstrated by ***Parisa Fallahi*** from **Basel Precision Instruments**. The lack of suitable low-noise, ultra-stable electronics for measurements of quantum devices at cryogenic temperatures led to development of dedicated instrumentation. The word-of-mouth spread and so they were selling their first products even before the company was founded.

Parisa Fallahi sharing the story and product line-up of Basel Precision Instruments. About 40 persons attended the session.

Next, ***Behzad Shirmardi*** explained how **BrightComSol** has evolved from a "startup incubator" and wants to replace common X-ray scintillators with novel perovskite nanocrystals. The challenge there is to achieve environmentally stable, large area thin films that then could be sold as OEM (Original Equipment Manufacturer) products to classical X-ray detector/scanner companies.

Stefan Radel from **usePAT** gave a very instructive and entertaining presentation about the struggles how to start up a startup. A set of founders with a complementary mix of skills and backgrounds was needed to take the idea of using ultrasonic fields to concentrate microparticles to successful products for inline gauges for industrial processes. Notably, the business side, with somebody who can build and execute a go-to-market strategy, navigate through the maze of intellectual property (IP) questions and lastly knows the language of finance and investors, should not be forgotten.

The support given by universities to spin-off companies has improved much over recent years, as ***Peter Buchberger*** from the **University of Innsbruck** highlighted. He rooted for entrepreneurship being taught as part of the curriculum. While founding your own company is probably the most exciting way to take an idea to a product, it is not the only one. In some cases, sensible alternatives are licensing, partnering and even (open access) publishing.

After the founding phase is over, the challenges shift towards expanding the portfolio and winning the battle for market leadership, as was showcased by ***Wolfgang Zesch*** from **Optotune**. Here, the protection of IP, with patents (that may be published) or with protected company secrets, move into focus. However, most of all, the challenge is to become profitable with the right and cost-efficiently manufacturable products.

The vibrant field of quantum technology was introduced by ***Mathieu Munsch*** from **Qnami**. From the idea in 2005 to use color centers in diamond for magnetic fields sensing on the nanoscale, to the first proof-of-concept in 2012, it took a lot more of development and testing to reach a robust and user-friendly, and moreover scalable, prototype in 2019. Mathieu shared important lessons about selecting the right team with complementary skills, the importance to gauge the value of IP and markets, and to plan ahead and think about strategic partnerships.

Wolfgang Lechner from **ParityQC** represented the very rare species of startups which go to market with a product from theoretical physics. They developed a hardware-agnostic quantum computing architecture. With a clever market and IP strategy and an experienced deep-tech investor on board, they could already license their concept to some of the players in the nascent field of quantum computing, in line with the credo: "If there is a gold rush, sell shovels." Focusing on market value to drive the development and selling of their quantum tools, they are targeting the fields of optimization, material simulation, machine learning and quantum chemistry.

The presentations on quantum technology startups were concluded by ***Juris Ulmanis*** from **AQT**, which are building ion-based quantum computers. While they are now pursuing a multi-tiered strategy ranging from quantum instrumentation over cloud-accessible quantum computers to on-premises quantum computers, he remembered that an igniting moment to start the business was when a guest in Rainer Blatt's lab asked, "Can I have one of your ion traps?".

In summary, the session spawned an interesting mix from "new-born" to "teen-age" physics-based startups. Their amazing stories and learnings were thrilling and insightful and should encourage to boldly put founding a company and entrepreneurship in general on the map of every physicist, and in any case, should at least bring joining a startup into the spotlight of graduating students.

Moreover, whereas the small selection of featured companies naturally only could provide a glimpse, it became very clear that startups are a major force to infuse and drive innovation. By bridging the so-called "valley-of-death" of innovation between academic ideas and real-world products, they establish important links between physics and society, and hence, in the end impact our everyday lives and are vital for a modern economy. An upcoming *SPS Focus* issue will take a deeper dive into this topic.

History and Philosophy of Physics (28)

100 Years ago: Nobelprize in Physics awarded to Albert Einstein

Hans-Rudolf Ott, ETH Zürich

It is not easy to fix the correct date for remembering this anniversary. In November 1922 the Nobel Commitee decided that Einstein should receive the Physics prize for the year 1921 and invited him to take part in the usual festivities at Stockholm in December of 1922. For reasons described below, Einstein was unable to follow this invitation but later agreed to acknowledge the receipt of the Prize by delivering a special lecture of his choice in July 1923, not in Stockholm but in Gothanburg instead.

The story around the Nobel Prize of Albert Einstein began in the first half of 1905. Although working full time, i.e., 48 hours a week, as a technical expert 3rd class at the Federal Patent Office in Bern, he submitted, within a little more than 3 months, four manuscripts for publication in the prestigious journal *Annalen der Physik*. In retrospect, the content of three of them was of exceptional scientific quality such as to qualify him for a Nobel Prize nomination. The fourth paper was actually his doctoral dissertation which he submitted to the University of Zurich at the end of April but appeared, a year later, also as a regular paper in the *Annalen*. His alma mater, the Federal Polytechnic in Zurich was, at the time, not yet allowed to grant doctoral degrees. A fifth manuscript, submitted somewhat later in that year, contains the equation $E = mc^2$, no doubt the most widely known relation in physics, even among the general public. Considering the circumstances, this scientific performance is absolutely amazing and in this connection the term *annus mirabilis* 1905 is well justified.

The titles of the three prizeworthy articles mentioned above are somewhat obscure for non-specialists. The first, submitted on 17 March, is entitled "*Ueber einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt*". In this work, Einstein got convinced that observations of the interaction of light with matter imply the existence of lightquanta, known today as photons. He deduced that the energy of individual photons only depends on the frequency ν of the radiation, i.e., $\varepsilon_{ph} = h\nu$, whereby h is the constant introduced by Planck in his pioneering work on the black-body radiation spectrum in late 1900.

With this hypothesis Einstein succeeded in explaining available experimental results concerning electrons emitted from metal plates by light absorption, also known as photoelectrons, as well as the well known Stokes' rule related to the photoluminescence of certain substances. The existing results of observations of both phenomena were, at the time, not understood on classical grounds, assuming that radiation is carried by Maxwell-type electromagnetic waves. In particular, Einstein concluded that the maximum energy of an individually emitted photoelectron was given by $\varepsilon_{el}^{max} = h\nu - P$, where P is the energy needed for the electron to leave the surface of the metal plate. The latter equation was later termed „the law of the photoelectric effect“. On classical grounds it was expected that this maximum energy would correlate with the intensity of the impinging radiation which, however, was not observed experimentally. Of course, Einstein realized the basic difference between the concepts of individual light particles and the very successful description of light propagation on the basis of Maxwell's electromagnetic waves. However, at that time he saw no way out of this dilemma, a fact that bothered him for years to come. In his own words, in a letter to a colleague, he judged his work as very revolutionary. As we shall see below, this view was well justified.

The second manuscript, entitled "*Ueber die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen*" was submitted on 11 May. In a theoretical study, Einstein investigated the motion of small particles suspended in liquids at rest on the basis of the molecular-kinetic theory of heat. He compared the results of his reflections and conclusions with the results of experimental observations and, in this way, achieved an indirect proof for the existence of smallest units of matter in the form of atoms and molecules, at the time still a disputed issue. Quite unexpected is Einstein's conclusion that an experimental determination of Avogadro's number is possible with a light microsope, still a truly amazing fact.

A masterpiece with respect to both new thinking and its presentation was the third article, submitted at the end of June and entitled "*Elektrodynamik bewegter Körper*". In it, Einstein formulated what he termed the principle of relativity which, among other things, requests that no physical experiment can verify the state of a body at absolute rest. For mechanical experiments this fact was known for a very long time. Einstein now postulated that, as a matter of principle, this also had to be true with respect to optical and other electromagnetic phenomena. In particular this implies that, in empty space, the speed of light cannot be varied by varying the motion of the light source, a conclusion that is only hard to grasp intuitively. It also follows that the simultaneity of events occurring at different sites in space is a relative concept and that time and space can no longer be regarded as independent of each other. This new point of view, summarized in the theory of relativity (later, after his creation of the *generalized theory* of relativity, Einstein termed his earlier theory of 1905 as the *special theory of relativity*), stirred the interest of highly regarded and competent colleagues and promoted Einstein's prestige rather quickly. The conclusion which Einstein regarded as the most important of this new theory, the equivalence of energy and mass in the form of the above mentioned equation, whereby E is to be understood as the rest energy of the mass m, was submitted for publication at the end of September 1905.

During the following year, in 1906, Einstein applied a generalized interpretation of the lightquantum hypothesis to explain a phenomenon related to thermodynamic properties of condensed matter. Following the findings of the previous year he saw the need to modify the classical perception of the molecularkinetic theory of heat in the sense that energy transfer can only happen via individual energy quanta. In this way he succeeded in finding an explanation for the up till then puzzling temperature dependence of the specific heat of solids well below room temperature. It is fair to state that in this way he also initiated the modern theory of condensed-matter physics.

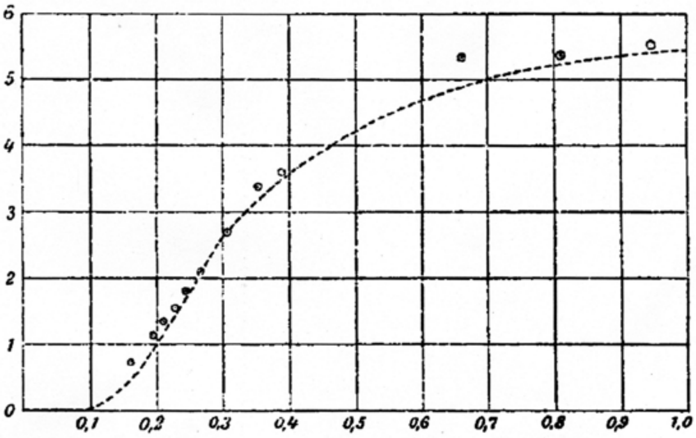

Fig. 1: Fit of Einsteins calculation of the temperature dependence of the specific heat C(T) of diamond. The experimental data (circles) are reported in H. F. Weber, Ann. Phys. ***154****, 367 & 533 (1875). Horizontal axis: x = T(k/hν); vertical axis y = C(T) in gramcalories. The best fit (broken line) is obtained with hν/k = 1300 K, with k denoting Boltzmann's constant.*

Because of all these pioneering contributions, Einstein, who had not yet reached the age of 30, was soon regarded by some, as one of the leading theoretical physicists, at least in Europe. It was therefore not surprising that, in 1909, he was invited to the annual *Versammlung Deutscher Naturforscher und Aerzte*, gathering in Salzburg in that year. It was expected that he would present his work related to the theory of relativity. Instead he chose to speak about the problem that really bothered him constantly and therefore his lecture, based on his earlier work in 1905 mentioned above, was entitled "*Zur Entwickelung unserer Ansichten über das Wesen und die Konstitution der Strahlung*". His presentation was met with severe skepticism or even rejection, however. The reason for this was mainly the obvious difference between the view of radiation as consisting of individual lightquanta or -particles and the very successful interpretation of light as Maxwell's propagating electromagnetic waves.

Another invitation, soon to follow in 1911, was to participate at the first Solvay Conference to be held in Brussels, sponsored by the Belgian industrialist Ernest Solvay. The meeting was intended to bring together a few but then leading scientists – Marie Curie was the only female person present – in order to discuss the most recent developments of the theories of heat and aspects of the then still new and much debated quantum physics. The participation of Einstein, only 32 years old, reflected his acknowledged competence in these fields and, indeed, he played a major role in the discussion sessions. Personally he judged the scientific content of the debates as not very enlightening because for him, nothing new emerged.

In retrospect the most important recognition of his contributions was the first nomination for the Nobel prize in Physics in 1910, submitted by the well known German physicochemist Wihelm Ostwald. Ten years earlier, Einstein had applied for an assistantship with Ostwald without success. Ostwald argued that the significance of the theory of relativity ought to be regarded as high as the discovery of the principle of energy conservation more the 50 years ago. During the following years up to 1920, with the exception of 1911 and 1915, Einstein was nominated for the Prize by different persons and with various justifications; none of them was successful, however.

Einstein's performance was also acknowledged in the academic sector with offers for professorships. He joined the University of Zurich (1909- 1910), the German University in Prague (1910-1912) and the Federal Institute of Technology (ETH) in Zurich (1912-1914). While at ETH, Einstein mainly collaborated with his former study colleague and now professor of mathematics Marcel Grossmann towards a General Theory of Relativity and Gravitation. A first draft (Entwurf) of the theory separated in two parts was ready in September 1913. Einstein was responsible for the physical part and Grossmann wrote the mathematical part. For various reasons they were suddenly in doubt, however, that they had found the correct form of the theory.

The offer to join the Prussian Academy of Sciences in Berlin, combined with a chair at the Friedrich-Wilhelm University, was the provisional climax of this part of his career. In this context it is remarkable that in the proposal to offer the membership of this institution to Einstein it is stated that his earlier light-quantum hypothesis should not be held against him too severely.

Einstein moved to Berlin in spring of 1914. On the occasion of his inaugural lecture at the Academy in July, his mentor Max Planck introduced him by acknowledging the outstanding scientific merits of Einstein but did not hesitate to question his then most recent work on General Relativity. For the second time, Einstein experienced a strong opposition against his innovative scientific ideas and the corresponding conclusions. Amazingly, the opinion of the scientifically most prominent colleagues concerning his light-quanta idea did not even change when Robert Millikan, in 1916, achieved an exact experimental verification of Einstein's law of the photoelectric effect mentioned above. Although Millikan himself had to admit the perfect matching between theory and experiment, he still didn't believe that Einstein's explanation made sense. He even claimed that to his knowledge, Einstein himself no longer believed in the validity of his explanation of the effect. Of course, this opinion was completely unsubstantiated.

In Berlin, after an exhausting intellectual struggle, Einstein finally succeeded in formulating the General Theory of Rel-

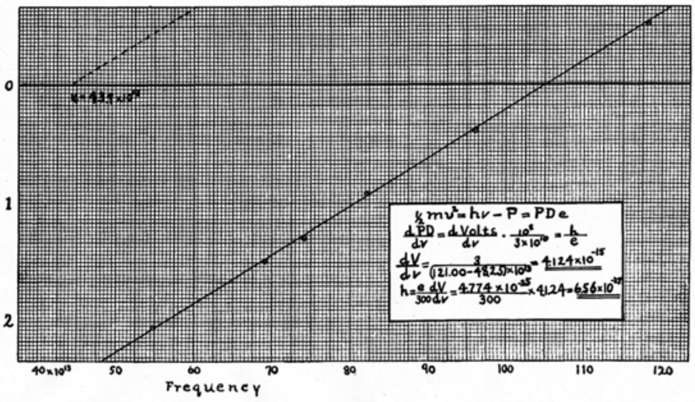

Fig. 2: Result of Robert Millikan's experimental determination of Planck's constant h. The diagram reveals the exact agreement with the law of the photoelectric effect (from Phys. Rev. VII, 355 (1916).

ativity and Gravitation in November 1915. The theory used mathematical tools that were not widely known at the time and therefore, only a few specialists were able to appreciate its content. One of the predictions dealt with the deflection of light rays by gravitational centres, i.e., masses. This phenomenon was verified in 1919. After the end of World War I, specially arranged astronomical expeditions of British teams under the auspices of the Royal Society in London set out to measure the deflection of star light by the sun during an eclipse. The collected data were claimed to quantitatively confirm the theoretical prediction and the result made a headline in the British newspaper *The TIMES* in November 1919. In this way, Einstein gained world wide prominence over night. Nevertheless, in spite of about 60 nominations over the years, he still hadn't achieved the status of a Nobel laureate. A growing number of prominent members of the scientific community expressed their amazement and it was felt that the situation became increasingly embarrassing for the Nobel Committee. The reasons for this situation are complex and are mentioned here only superficially.

According to the last will of Alfred Nobel, each year the Prize should go to persons whose accomplishments in the disciplines Physics, Chemistry, Medicine, Literature, the pursuit of Peace and, later added, Economics, has conferred the greatest benefit to mankind. Considering this condition, it seems then quite natural that accomplishments in theoretical and mathematical physics, Einstein's principal fields of activity, are difficult to judge in this respect and may not get elected to be awarded. These difficulties in connection with the Physics Prize are somewhat reflected in the fact that the responsible committee chose to postpone or even skip the award in several years between 1915 and 1920. The latter happened in 1916. In several of the following years up to 1921, the allocation of the prize was first postponed and finally awarded later. Only Charles Edouard Guillaume (1920) and Niels Bohr (1922) obtained the prize in the regular cycle. In the case of Einstein, the committee decided in November 1922 to bestow the prize to him for 1921 by honouring his contributions to theoretical physics in general and, in particular, his discovery of the law of the photoelectric effect.

In September 1922, Einstein was, in a subtle way, alerted that he might get the award later in the year. In a letter, the Nobel committee member Svante Arrhenius asked Einstein to save the time for a visit to Stockholm in early December but added that an official invitation was not to be expected before the 9 November. At the time, Arrhenius was aware that Einstein was planning a longer excursion to Japan and asked him to revise his travel plans. For various reasons, Einstein did not intend to change his plans and, in his return letter, informed Arrhenius to this effect. Nevertheless he expressed his hopes that the invitation would only be postponed and not altogether cancelled.

Together with his wife, Einstein left Berlin on 3 October 1922 and traveled via Zurich and Geneva to Marseille where on 6 October, they boarded the Japanese steamship SS Kitano Maru. On their sea travel they passed the Suez canal and headed, via Colombo, Singapore, Hongkong and Shanghai on to Kobe. On 10 November they reached Shanghai where Einstein, via telegram, was informed that he was chosen to receive the 1921 Nobel Prize for Physics and any further information would be transmitted by letter. Although it is quite certain that this news pleased him very much, it is not mentioned in his otherwise quite detailed travel diary. In a further letter dated 11 December and sent to an address in Japan, he was also informed about some details of the financial aspects of the prize. Einstein responded to these informations by a short letter to Arrhenius only on 10 January 1923. At the time he was already on his return travel back to Europe in the region of Singapore. The letter was written on stationary of the SS Haruna Maru. One sentence of this letter reflects Einstein's feelings with respect to his being awarded with the Nobel Prize in an amusing style: „*I am very glad to have received the Nobel Prize – also because there is no longer any reason for people to ask me the accusing question: Why don't you get the Nobel Prize? (My usual answer is: Because it is not I who can award the Prize)*". Along his return, Einstein also payed short visits, each lasting a few days, to Israel and Spain.

Arrhenius responded to that letter on 17 March. He informed Einstein that the insignia of the Prize in the form of a gold medal and a certificate had been received by the German ambassador in Sweden on the occasion of the regular festivities on 10 December in Stockholm [1]. In addition he suggested to organize a special reception event for Einstein during a grand Scandinavian exhibition in Gothanburg on the occasion of the 300th anniversary of this city. There Einstein would deliver a lecture which would be attended by the

KUNGLIGA SVENSKA VETENSKAPS-AKADEMIEN

ALFRED NOBEL

ALBERT EINSTEIN

Fig. 3: Certificate of Einsteins's Nobel Prize

Fig. 4: Einstein's delivery of his „Nobel lecture" in Gothanburg in July 1923.

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[1] after Einstein's return to Berlin, the medal and the certificate were delivered to him personally by the Swedish ambassador in Germany Baron Ramel.

Swedish King Gustav V. This is indeed what happend on 11 July 1923. Since the Lecture was not delivered on the occasion of the usual Nobel Prize ceremony, the topic was not on the discovery for which the Prize was awarded. Instead, Einstein chose to speak on "*Grundgedanken und Probleme der Relativitätstheorie*".

By covering the story of Einstein's Nobel Prize, a brief comment on its role in connection with the divorce of Einstein from his first wife Mileva Maric is in order. Mileva and Albert got married in January 1903 in Bern. Since summer 1914, she and their two sons Hans Albert and Eduard lived in Zurich, separated from Albert in Berlin [2].

On 31 January 1918, Albert had asked Mileva for the second time to submit a libel for divorce with him as the guilty part and, as encouragement, offered her some financial advantages. In order to secure the financial support of his former family, he offered her to receive the prize money of the Nobel award, should he ever be the recipient, Following a series of letters back and forth during the first half of 1918, as an advance measure, Albert deposited 40'000 Reichsmark (RM) in securities with the Schweizerische Bankverein in Zurich and an additional 20'000 RM with a Bank in Berlin, both in favour of Mileva if she agreed to a divorce. At the same time he requested Mileva to now submit the libel for divorce and to send him a draft of the divorce agreement that they had discussed previously. In early June this finally resulted in a draft of the document to which both sides agreed. At the beginning of November, Albert agreed with the suggested modus of payment but, for the first time mentioned his hope that his financial capabilities would not suffer too much in the aftermath of Germany's lost war.

On 14 February 1919, the trial before the Bezirksgericht Zürich, also attended by Albert, took its course and the divorce was officially executed. The financial aspects were part of the decision. Important in this respect was the deal that Mileva had no direct access to the deposit without the consent of Albert but was entitled to use the interests.

In the course of 1919, the exchange rate of the Reichsmark with respect to the Swiss Franc worsened dramatically. On 15 October, Albert informed Mileva that he could no longer meet the contractually agreed money transfers in Swiss currency. His somewhat unrealistic suggestions of how to solve the problem were, after some fierce intervention by Mileva, postponed for the time being.

The problem was finally solved when, as described above, Einstein indeed received the Nobel award. The prize money of 121'572.54 Swedish crowns was transferred to a special account with the Enskilda Bank in Stockholm on 11 December 1922, while Einstein was still in Japan. At the time this amount represented the equivalent of approximately 49 annual salaries of Einstein in Berlin! In order to avoid exchange-currency losses, the money was finally deposited with Banks in Zurich and New York. The former amount was later used to buy an apartment house in Zurich. The expected rental income was to secure the living costs of Mileva and their two sons.

Viewed in this light, the allocation of the Nobel Prize 1921 was not only a well deserved recognition of the scientific achievements of Einstein. It also prevented his threatening financial ruin and the prize money secured the financial support for his former wife and, his main worry, for his children and their education.

The content of this article is based on information taken from volumes 2, 8B, 9 and 13 of the **Collected Papers of Albert Einstein** (CPAE), published by Princeton University Press and the book of Abraham Pais, „**Subtle is the Lord**...", The Science and Life of Albert Einstein, first published in 1982 by Oxford University Press.

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[2] in the course of their separation in 1914, Mileva refused to agree to a formal divorce.

Pre-Announcement: Albert Einstein Symposium 2022

It has by now become a tradition that the SPS organizes a symposium between its annual meetings. The symposium commemorates an important event or person in the history of physics. After Richard Feynmann (2018), Georges Lemaître (2019) and Wilhelm Conrad Röntgen (2020/21) the 2022 symposium is planned to celebrate the centenary of the Nobel Prize for Albert Einstein.

In November 1922, it was announced that Einstein receives the Nobel Prize of 1921. The prize was awarded to him "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect." So interestingly, there is no mentioning of both the Special and the General Theory of Relativity; rather the main reason given for honoring Einstein is his 1905 explanation of the photoelectric effect. It took more than 10 years to experimentally confirm Einstein's bold hypotheses. Einstein was not able to come to the award ceremony in Stockholm and only received the prize in July 1923 at a meeting of the Nordic Assembly of Naturalists in Gothenburg.

Since Einstein was mainly awarded the prize for a paper that he had written during his "*annus mirabilis*" when living in Bern, the symposium will take place in Bern:

9 April 2022, 10 – 17h
UniS, Schanzeneckstrasse 1, 3012 Bern,
Lecture hall S003

The symposium will start with providing the historical background and then move to modern developments of photonics.

The detailed program will be published on the webpages of SPS, SCNAT, and the Albert Einstein Society Bern (both our co-organising partners), as well as in the next issue of the *SPG Mitteilungen*. Please save the date for this exciting event!

Claus Beisbart, Chair of the HoPP Section

Young Talent Day and Röntgen Symposium: a sparkling and fruitful mix of generations

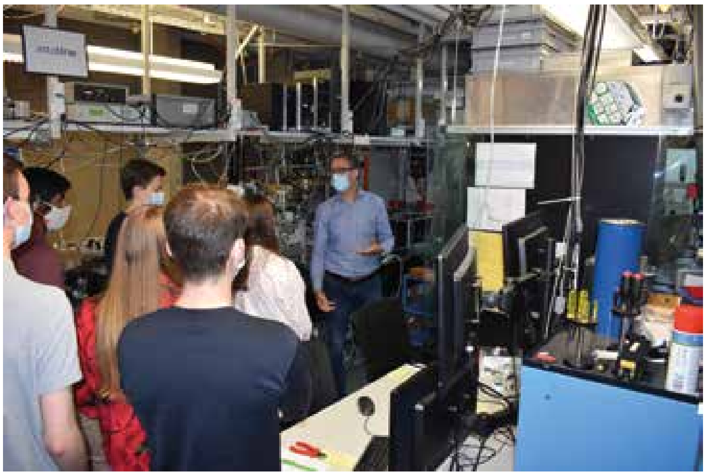
Lukas Gallmann, Antoine Pochelon

As announced in last issue of the *SPG Mitteilungen*, a special symposium celebrating the 175 + 1 year after Wilhelm Conrad Röntgen's birth took place on the Hönggerberg campus of ETHZ on 18 September. The reputable speakers and exciting scientific content of this open symposium that highlighted the history and broad impact of Röntgen's discovery attracted a large number of attendees [1]. Lesser known to most, we used the opportunity provided by this event to invite a number of young physics talents to ETH. Besides exposing them to the scientific presentations of the afternoon symposium, we offered them a first taste of modern laboratory-based physics research in a number of laboratory visits in the morning of the same day.

For some years now, the SPS has been inviting young people who have distinguished themselves nationally and internationally in Physics Olympiads or Tournaments [2] to attend laboratory visits and conferences. We invited 43 students from competitions in 2020 and 2021, as the event couldn't be organized in 2020. There were finally 24 participants, 4 young women and 20 young men, mainly from the gymnasial level. Some of them couldn't participate, as they have already started their studies abroad in the US or UK.

The different competitions promote different skills. The Olympiads take the form of an individual examination, whereas tournaments encourage oral jousting between teams for defence, opposition and synthesis on prepared questions, which involves a lot of consultation among the team. In the case of SJF, it is the development of a thematic research, carried out by an individual or a pair. A fascinating example of such individual work in the latter context is the development of a PID stabilisation system, stabilising a ball launched on a tablet, see video (video: https://www.youtube.com/watch?v=57DbEEBF7sE), a task which involves building the motorised tablet (tablet: https://github.com/JohanLink/Ball-Balancing-PID-System/blob/master/TM_SJF_version.pdf) and programming the feedback.

Just to mention one performance among many others, the SYNT team (12 - 16 years old) brought home some very nice laurels by winning the gold medal with the first place out of 14 competing teams at IYNT 2020 in St. Petersburg. And it is not the first time the Swiss YNT team reaches gold! It is also remarkable that the involvement of some young people in Olympiads sometimes goes far beyond physics alone: there are some young people who did participate to 3 and even 6 different thematic Olympiads.

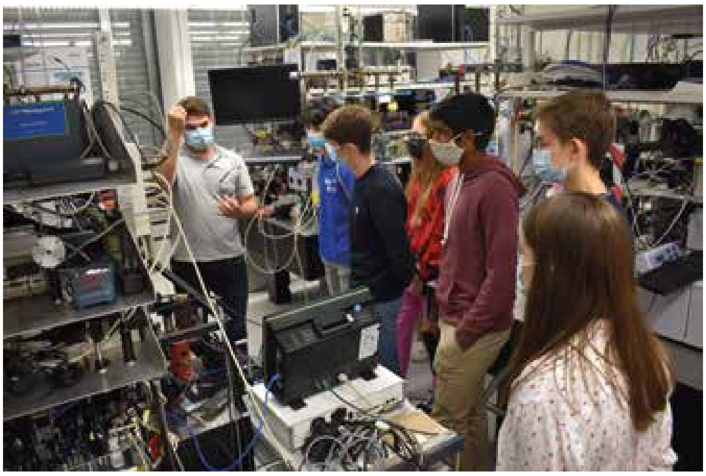


Prof. Lukas Gallmann explains research in his the attosecond laboratory.

The laboratory visits were a clear first highlight for the young people on that day. The young talents visited 3 different laboratories, guided by professors Thomas Ihn (Nanostructures), Lukas Gallmann (Attosecond science) and Giacomo Scalari (Quantum Optoelectronics). In parallel to the laboratory visit, Thomas Ihn showed some "curiosity-inspiring" or "mind-opening" objects, like the object of total curvature zero resembling a sea-sponge in the figure; or a system of suspended springs and ropes carrying a weight, which surprisingly moves up when cutting a link, as nearly everybody expects it to move down. These demonstration objects are nice excerpts from their "lab apple club", giving a facet of the research atmosphere in this group.

Everywhere zero-curvature surface

In the afternoon, the Röntgen Symposium covered the subject of X-rays with five magistral talks, from the history of their discovery to present-day sources and applications.



Visit in Prof. Giacomo Scalari's quantum optoelectronic lab.

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[1] The abstracts have been published in the *SPG Mitteilungen* Nr. 64, p. 55, https://www.sps.ch/fileadmin/doc/Mitteilungen/Mitteilungen.64.pdf

[2] SwissPhO (Swiss Physics Olympiad), IPhO (International Physics Olympiad), EuPhO (European Physics Olympiad), SYPT (Swiss Young Physicists' Tournament), IYPT (International Young Physicists' Tournament), SYNT (Swiss Young Naturalists' Tournament), IYNT (International Young Naturalists' Tournament), IPT (International Physicists' Tournament), SJF (Schweizer Jugend Forscht), and exceptionally guests from NBPhO (Nord Baltic Physics Olympiad) and BL4S (Beam Line for Schools); see also "An Overview of Physics Olympiads and Tournaments at gymnasial and university level, national and international", A. Pochelon, L. Gallmann, C. Boinay, S. Byland, E. Glushkov, *SPG Mitteilungen* Nr. 58, July 2019, 51-54.

Participants of the Young Talent Day just after the visit of three research laboratories at ETHZ Hönggerberg.

Prof. Ralph Claessen from the University of Würzburg presented an insightful and entertaining view of Röntgen's life and the history of his epoch-making discovery. Prof. Marco Stampanoni from the University of Zürich and PSI then impressed the audience with an overview of the capabilities of state-of-the-art X-ray imaging techniques, including the example of a microscopic X-ray tomography of a living and flying drosophila fly with temporal and high spatial resolution. Representing Dectris Ltd., a world leader in X-ray pixel detectors, Dr. Clemens Schulze-Briese put a particular emphasis in his timely presentation on how modern X-ray imaging techniques enabled unravelling the structure of COVID-19 and the development of the related vaccines. A talk focused on X-ray sources that are situated in scale in-between X-ray tubes and modern free-electron lasers, PD Dr. Davide Bleiner from EMPA introduced the audience to the physics of table-top X-ray lasers. The symposium was then concluded with an inspiring overview of modern X-ray astronomy by Prof. Stéphane Paltani from the University of Geneva. The symposium attracted a broad audience of over 80 participants. The presentations were exciting, of excellent professional level and are available on the SPS website[3].

The young people demonstrated a sustained interest by a large number of questions addressed to the expert presenters of the symposium, giving a sane vitality to the debates. Merging the YTD with the symposium was an excellent idea, as it provided an in-depth view of a highly relevant research topic in physics, thus giving a strong scientific backbone to the event for the youngsters.

The returns were also very rewarding:

> *"I really enjoyed the day, especially the lab tours. The professors explained their research well."*
>
> *"This day allowed me to visit a part of the ETH campus and especially, to see in detail some physics laboratories where particularly interesting technologies are developed. These visits were also accompanied by very clear explanations given by fascinating professors. The YTD day more than fulfilled my expectations and I thank you once again for inviting me."*
>
> *"I left the Röntgen Symposium with a good number of new topics to learn about and research with regards to X-Rays as well as topics regarding the research in the laboratories."*
>
> *"This day has indeed somewhat fulfilled my expectations, with captivating and educational visits. If one sentence were to sum up the day, it would be 'A wonderful first step into the world of engineering with the link between the elegance of physical equations and the reality of the world around us'."*

All were thankful for the opportunity and organization.

The spirit of this event is to allow young people to visit different laboratories at the conference venue, to have them meet professional physicists in a research or lecture situation so that they feel the atmosphere of a life as a researcher. This is essential as research requires additional skills to those that are conveyed in the classroom. It can only be beneficial to become aware of this as early as possible, and whenever possible, even before starting a university course. Last but not least, the event is also an excellent opportunity to bring young, highly motivated and similarly-minded people together.

This day was organised by SPS, together with the Physikalische Gesellschaft Zürich (PGZ), with the support of the Academy of Natural Sciences (SCNAT), which allows the SPS to support the students for transport and meal and also the Röntgen symposium as a whole. There are agreements on prizes awarded by the SPS with SwissPhO (Science Olympiads) and with SJF. SPS also supports participation in the IPT.

The speakers of the Röntgen Symposium: Ralph Claessen, Marco Stampanoni, Clemens Schulze-Briese, Davide Bleiner and Stéphane Paltani.

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[3] https://www.sps.ch/events/diverse-veranstaltungen/weitere-symposien-und-fruehere-anlaesse/wilhelm-conrad-roentgen-symposium

The Kids are all bright – the 27th Edition of the Swiss Physics Olympiad

Luc Schnell, SwissPhO

Carrying out a Physics Olympiad with more than 700 students from all over Switzerland and Liechtenstein during an international pandemic seems a bold endeavor. But after this year's edition of the Swiss Physics Olympiad with all three rounds held in an online format and witnessing the unwavering enthusiasm for physics of the students, we can proudly say that it is possible. Continuously adapting to the situation, both the students and the volunteers did not let the virus be an obstacle for sharing our passion for physics together.

It all started in September 2020. As usually, the students solved the problems of the first round in their classrooms or on a computer at home. 130 students were invited for the training in autumn and the second round. Under normal conditions, we could all meet during a one-week preparation camp in November and go through the material of the second round together. This year we had to change our plans. The preparation camp was modified to an online challenge month during which we provided online coaching sessions as well as problem challenges. Also the exams of the second round had to be held online. Despite this year's edition requiring more effort and self-study from the students, their motivation seemed not to be deterred and 26 students qualified for the final round.

Hoping that at least the training camp in January and the final round could be held online, we were disappointed yet again. But by then we knew what to do. We switched the second training camp to an online challenge mode and opted for an online version of the national finals on the 20th and 21st of March. With the help of our volunteers, among who we are happy to count multiple past participants and high school teachers, we could provide the students both with interesting theoretical problems as well as an experimental task. The former included tough questions about oscillations in a U-tube, thermodynamic changes of state and eddy-current brakes in trains. For the experimental part, we shipped packages containing all necessary material to the participants. They were asked to build a physical pendulum consisting of a common chopstick. Via the oscillation period, the location of the stick's center of gravity could be determined in a precise manner. All in all, the exams lasted for 6.5 hours distributed over two days.

Screenshot from this year's award ceremony of the Swiss Physics Olympiad finals. As the exams, also the ceremony had to be carried out virtually. The excitement with which the results were awaited was however the same.

Kylian Gauteron (top) and Valentin Hächler (bottom), the winners of the "SPG Nachwuchsförderpreis / Prix de la Relève de la SSP".

In the end, **Kylian Gauteron** from the Lycée-Collège des Creusets (VS) and **Valentin Hächler** from the Gymnasium Oberwil (BL) achieved the first and second place with their brilliant performance, winning gold medals. They were also awarded the *Nachwuchsförderpreis* / *Prix de la Relève* generously sponsored by the SPS. The remaining gold medals went to Raphael Burkardt, Andres Neff and Mathieu Zufferey.

While this concluded the national competitions, the international ones were only getting started. The European Physics Olympiad (EuPhO) took place in June, followed by the International Physics Olympiad (IPhO) in July. Also these events had to be carried out remotely, the Swiss teams met up at the University of Bern and a camp house in Signau (BE) to solve the exams virtually. Raphael Zumbrunn was awarded a bronze medal (IPhO), Kylian Gauteron, Mathieu Zufferey, Valentin Hächler and Anastasia Sandamirskaya achieved honourable mentions (3 x IPhO, 1 x EuPhO). This shows that these young talents were able to defy all odds that this year has thrown their way.

We have not given up hope that the coming edition of the Swiss Physics Olympiad can be held normally and that we will be able to all meet in person. But even if not, we can say one thing with certainty: The kids will be all bright.

Review of the 2021 Young Physicists Forum: Exoplanetology

Toni Berger [1], Edwin Genoud-Prachex [2] and Anna Lüber [3]
[1] Universität Basel, [2] Université de Genève, [3] Universität Bern

This year, the committee of the Young Physicists Forum (YPF) organized a series of lectures focusing on "Exoplanetology" during the weekend of the 24th and 25th of April. Due to the COVID-19 pandemic, the event had to be carried out online. Registration was possible for all physics students of Swiss Universities as well as for everyone else interested in joining. There was no participation fee because of the purely online organization.

2019 was a very important year for the science of exoplanets: on 10th of December, Professors Michel Mayor and Didier Queloz from the University of Geneva received the Nobel Prize in Physics "*for the discovery of an exoplanet orbiting a solar-type star*", while on 18th of December the European Space Telescope CHEOPS led by the University of Bern was launched from Kourou. Thus, we have chosen to organize a Forum about exoplanetology during Spring 2020 at the University of Bern (Leading House of the NCCR PlanetS).

Several professors working in the field were enthusiastic about participating. However, because of the 2020 spring containment, this Forum was postponed to 2021 [1]. Most of the invited professors were still interested in participating in the event, but unfortunately, some were no longer available at the event's date and recommended PhD students or senior researchers working in this exciting field of Physics. Which was in fact an interesting opportunity: while the professors were evidently very experienced in giving lectures to a broad group of students, the PhD students could be more relatable to the participants and give recommendations about starting studies in the field of exoplanetology.

Soon there was a healthy mix of eight lecturers willing to show their research and let the students dive into the realm of exoplanets. The lectures were distributed in two one-hour lectures per half-day, with enough time to let the participants ask questions about the conference itself and the respective research.

The students were invited to participate by sending an invitation email to physics student associations of all Swiss Universities, which they thankfully shared with their students. Since there was no upper bound on how many people could participate in the online lectures, we let the registration open until the day before the event started. Between 20 and 35 participants joined each lecture. The number of participants was good for an online Forum compared to previous in-person events, where we were able to welcome 40 participants.

We were also happy to see some known faces from previous Forums. While there were students who joined every lecture, there were also students who just wanted to listen to their favorite lecturer or favorite subtopic, and therefore just joined a few of the available lectures. For every lecture, a committee member introduced the lecturer, while at the end, participants asked many interesting questions: often the lectures lasted for more than one hour! Fig. 1 shows a few participants, including a lecturer and committee members (instead of a classical group photo, we have a Zoom screenshot of the camera turn-on participants!).

Fig. 1: Screenshot of the Zoom lecture of Claudio Valetta (top right) with committee members and participants. From left to right and from top to bottom: Anna Lüber, Toni Berger, Claudio Valetta, a participant from Berlin, Luna Bloin-Wibe, Edwin Genoud-Prachex, Johannes Eberle [Frederik Van der Brugge (the last committee member) is missing in this group picture].

At the beginning of the event, on Saturday 24th of April, the YPF committee welcomed the participants and shortly introduced themselves, explaining the idea behind this year's event and its organization. The Saturday lectures focused on the detection and characterization of exoplanets.

The starting lecture was given by Prof. Sascha Quanz (ETH Zürich), with the title "Towards the direct detection of terrestrial exoplanets". He reviewed some of the highlights in exoplanetary science, described the existing detection methods, and illustrated a roadmap on how to directly detect and characterize a large number of terrestrial (and possibly even Earth-like) exoplanets in the coming decades.

Dr. Andrea Fortier, Instrument Scientist for the CHEOPS (CHaracterizing ExOPlanet Satellite) Science Team at the University of Bern, gave a presentation with the title "CHEOPS and its latest results/discoveries". She presented a review of the discoveries of exoplanets. The rapidly growing number of discoveries emphasized the need for characterization of these exoplanets and thus the launch of CHEOPS, which acquires images allowing for precise measurements of exoplanets' radii through the transit photometry technique. Dr. Fortier further gave an overview of the CHEOPS construction phase, its challenges, and its current operation. Fig. 2 shows some characteristics of the CHEOPS satellite.

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[1] The 2020 Forum was organized online in September 2020 and focused on "Interdisciplinary Physics", see the article in: *SPG Mitteilungen*, Nr. 63, pp. 44-45.

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CHEOPS

CHARACTERIZING EXOPLANET SATELLITE

A jointly Swiss + ESA led satellite
CHEOPS Consortium:
Switzerland +
10 European countries

- Reflector telescope (Ritchey-Chrétien type), 30 cm aperture
- High-accuracy transit photometry on single targets
- Quality over quantity: high precision photometry on a relatively small sample of well selected targets

CHEOPS Budget
Total cost ~100M€

Fig. 2: Slide of Dr. Andrea Fortier that shows the main characteristics of the satellite CHEOPS. © Andrea Fortier

Chloe Fisher, PhD student at the University of Bern, gave a lecture entitled “Studying Exoplanet Atmospheres from Earth and Space (with Machine Learning)”. She described the characterization of exoplanetary atmospheres and described the methods to study these atmospheres by using data from both space and ground-based telescopes. She highlighted a machine learning method known as “Random Forest” and explained how to use it to advance the analysis of exoplanet atmospheres.

The last lecture on Saturday was held by Prof. Francesco Pepe (University of Geneva). His presentation, “Exoplanets: From the first detection to their characterization”, was a perfect mixture between a summary of previously discussed topics and an introduction to more observational techniques used in exoplanetary science. The historical overview he gave was focusing on how, during the past 15 years, the domain of exoplanetary sciences extended to the detailed characterization of the exoplanets’ dynamics, composition, as well as their atmospheres, made possible by the refinement and improvement of observational techniques.

The four lectures given on Sunday 25th of April focused on planet formation, including theoretical, numerical, and historical aspects incorporated in this topic and on the habitability of exoplanets.

On Sunday morning, the first lecture was given by Claudio Valetta, PhD student at the University of Zürich, who is currently studying the evolution of giant planets with heavy-element enrichment. His lecture, “Planet formation: How do planets form?” described the current understanding of how planets are formed, what planets are made of, and what controls planetary diversity. This young field of research is still rapidly evolving and many questions remain unanswered. This is an important aspect, which could motivate students to start their PhD or Master’s thesis in this exciting field.

Prof. Christoph Mordasini (University of Bern) held a presentation whose title was “Testing planet formation and evolution theory with observations of extrasolar planets”. He started his lecture with an overview of some of the most important observational constraints before describing how the “distillate” of results from theoretical models of the physical processes governing planet formation can be combined into a comprehensive model, describing the formation and evolution of entire planetary systems from the origins to the present day. He explained how the results of such models are confronted with reality via comparisons on the empirical distribution of extrasolar planets considering the relevant parameters, uncovering many discrepancies. Thus, he was pointing at the shortcomings of the current understanding and identifying where future research should be developed.

The lecture series continued with Prof. Brice-Olivier Demory (University of Bern). He started his presentation on “The quest for habitable worlds and a look back at Earth” by describing the recent breakthroughs in exoplanet science including the detection of the *Trappist-1* system. He detailed the prospects of characterizing life in our solar system and beyond within the next decade before continuing to present a new experiment currently in the design phase, aiming at demonstrating the remote detectability of bio-signatures by using spectro-polarimetry. He explained how applications using this technique include novel research in Earth remote sensing and could even revolutionize brain cancer diagnosis and staging techniques. Fig. 3 compares the *Trappist-1* system with the Solar System, showing especially the circumstellar habitable zone (in green).

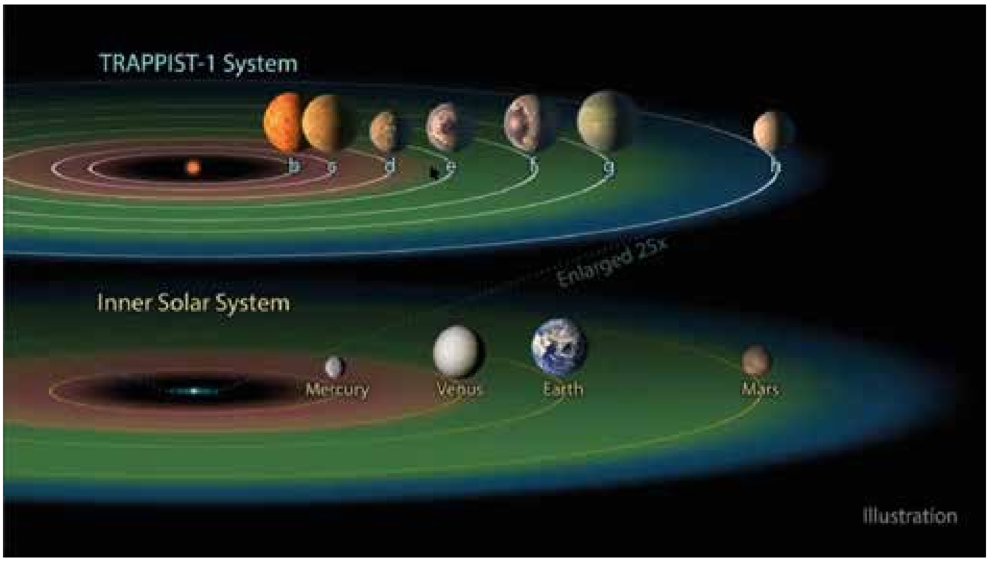


Fig. 3: Slide of Prof. Brice-Olivier Demory that shows the comparison between our Inner Solar System and the Trappist-1 system. The distances are enlarged 25 times for the Trappist-1 system with respect to the Solar System. In green, the circumstellar habitable zone. © Brice-Olivier Demory

The closing lecture was given by Marco Cilibrasi, PhD student at the University of Zürich. His lecture was titled “State of the art of the theoretical and numerical side of planet formation”, in which he showed the early theories and results that provided a first understanding of the formation of giant and terrestrial planets. He mentioned the newest findings, involving even the formation of moons and rings. He focused on the techniques and methods used in the community and especially at the ETHZ and University of Zürich.

After these two days with eight fascinating lectures, it was then time to close this journey into the discovery and characterization of exoplanets and their related topics. We saw that it is a very hot subject with a lot of discoveries done and still to be done. The next step is to search for extraterrestrial life, and, maybe someday the journey towards exoplanets will not be purely imaginary anymore! To thank our lecturers for their time and availability to share their passion and knowledge, we offered them boxes of chocolates. We also were very happy to see so many participants interested in discovering more about exoplanets and asking many interesting questions to the lecturers.

We may note that it is a real proof of interest and motivation that students want to follow Zoom lectures in their free time while they have been doing their entire studies in an online format for over a year. This past year has not been an easy one for studying, but the demand to learn more about science is still here! The online aspect of the Forum allows us to offer a free weekend accessible from everywhere, but this positive point does not fully counterbalance the loss of social communication during the Forum, which is generally full of discussions about physics, the Universe, life, and everything.

More information about this 2021 Exoplanetology Forum (including lectures' recordings and abstracts as well as lecturers' biographies) can be found on our website: *www.young-physicists.ch/forum-2021*. We also thank all our lecturers for allowing us to share the recordings of their lectures.

The next Forum is planned to be organized during Spring 2022 (if possible as an in-person meeting in a Swiss physics laboratory), by a slightly different committee: EGP and AL will leave their places after respectively 3 and 2 years in the committee to start their doctorates. New members are then going to be welcomed! We already have a lot of ideas for topics for our next Forum in 2022! Detailed information and registration will be available from the beginning of 2022 on our website: *www.young-physicists.ch*.

International Physicists' Tournament in times of the pandemic

Evgenii Glushkov, EPFL, Swiss representative and Vice-President of the IPT, evgenii.glushkov@epfl.ch

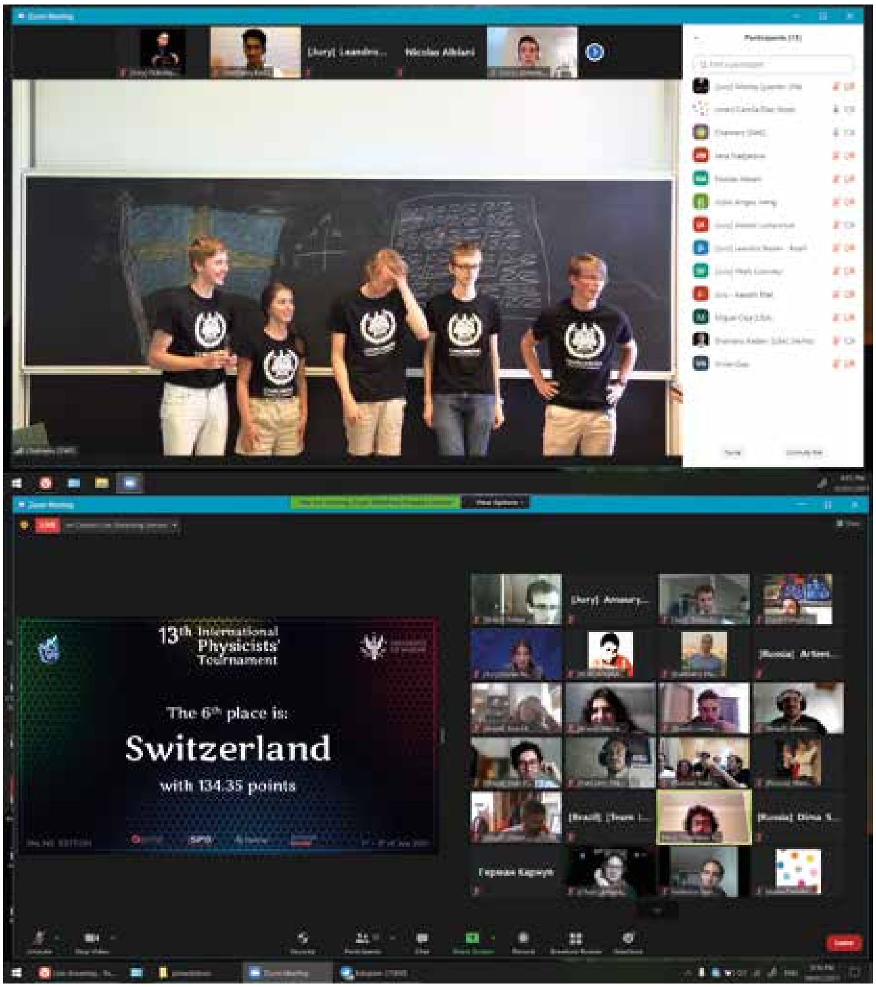
When COVID hit us back in March 2020 and most of the world came to a standstill, we were actively preparing the IPT 2020, which was supposed to take place at the University of Warsaw in April that year. Almost 20 registered teams, 200 participants and jurors, an amazing week full of educational and social events – it all suddenly hung in air. Not fully realizing the scale of the pandemic at that time, we first hoped for a quick recovery in summer and rescheduled the tournament to the end of June. But in a couple of months it became obvious, that even though strict lockdowns were slowly being lifted in many countries, it would be impossible for teams to travel to Poland (or any other location). Therefore, we had to quickly come up with alternatives...

The author demonstrating one of the prizes for the winners of the IPT 2020.

Just cancelling the event was not an option – dozens of teams around the world have worked for several months trying to come up with convincing solutions for the traditional list of exciting IPT problems! So, following the lead of many other postponed events, we decided to make an online version of the IPT in September, once students were back from summer holidays. This additional time was also needed for the organizing committee to explore the available platforms and sort out the details of running such an event in an online setting.

Naturally, we explored various options. From the onset of the lockdown new solutions for remote meetings and conferences started popping up, offering improved interactivity, compared to traditional video messengers. However, most of these platforms were quite costly and still under development. So, after several unsuccessful negotiations for educational discounts with various vendors, we decided to host the IPT 2020 on Zoom, which became a de-facto communication standard by then, commonly available through university licences. This also meant that there will be one less barrier for our participants to use the platform during the event, as they've most probably used it already for their online classes.

The rest was all details. We shrunk the typical 1-week long event into two full weekend days, made a clear schedule with hyperlinks to direct the IPT participants to the different Zoom rooms and defined a chairperson in charge of every room. A harder task was to pick the start and end time of the Physics Fights, suitable for teams both from Asia and America, but some compromise has been eventually found.



13th International Physicists' Tournament

The 6th place is:

Switzerland

with 134.35 points

Screenshots of the Swedish team presenting at the IPT 2021 through Zoom (top) and the online awards ceremony of the IPT 2021, showing the result of the Swiss team, represented by the students from ETH Zürich (bottom).

In addition to the six hours of preliminary rounds on Zoom (which now could be easily recorded unlike at the offline event), we also broadcasted the 5-hours-long IPT Final on YouTube, attracting thousands of viewers from all over the world! Needless to say, it was a very intense and fun weekend both for the participants and organizers!

We didn't stop here. During the subsequent week we also held an online IPT Conference, where participants of the IPT 2020 could present the solutions, on which they worked during the last year (typically, only 3-4 solutions out of 17 can be presented during the tournament itself). That allowed for even larger dissemination of IPT results and an increased scientific interaction between the students from different countries who have worked on the same problem. However, in comparison to the traditional tournament from last years the social interaction was definitely missing, as well as the pleasure of travelling as a team to another country.

While the latter was hard to compensate in times of COVID, the improved social interaction and immersion into the virtual IPT experience became our goal, as organizers, for the IPT 2021, once we realized that it had to be held online as well. This time we not only had more time to prepare the event, but also a strong support from a group of students and professors from the University of Warsaw, where the original event has been planned to take place. This group of local organizers not only created an online environment reminiscent to their university building (on the gather.town platform), but also prepared plenty of social activities (games, lab tours, quizzes, etc.) for the participants to enjoy. Therefore, the tournament was spread over 4 days (Thursday to Sunday), leaving sufficient time for interactions between the students from various teams.

Even though we still held the Physics Fights through Zoom as a well-known and reliable solution, the existence of a common virtual platform with a gamified interface helped bringing the participants together in between the Fights. This was the common space that was definitely missing back in 2020, allowing for both one-on-one interactions and group conversations (both via text, audio and video messages). And even though we couldn't possibly bring the students from different countries to one physical location, we definitely managed to bring back part of the unique IPT spirit, stemming from the cultural and scientific exchange between participating teams!

Definitely, no online event can fully replace the experience and excitement of a traditional IPT week, so we are still hoping to be able to organize an in-person meeting in 2022. But even in case the restrictions in place do not allow for that – we are all prepared now to face the challenges of organizing an online physics tournament! With latest technological developments we can continue to fulfil the core mission of the IPT – bringing together teams of passionate physics students from all over the world to solve puzzling questions from everyday life, advance the human knowledge together, and become the next generation of scientists and researchers for the brighter future ahead!

If you would also like to join the IPT adventure, either as participant, jury member or volunteer, please check out our website iptnet.info or write directly to the author.

Pre-announcement: SPS Annual Meeting 2022

The next annual meeting will take place at the ***University of Fribourg***, ***27 - 30 June 2022***.

The well established tradition of collaborating with CHIPP will be continued, possibly again with contributions from further partners.

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 2022, as well as on our website.

Ausschreibung der SPG Preise für 2022

Auch im Jahr 2022 sollen wieder SPG Preise, die mit je CHF 5000.- dotiert sind, vergeben werden.

- SPG Preis gestiftet von der Firma *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* 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**
- SPG Preis gestiftet von der Firma *Hitachi Energy Switzerland AG* für eine hervorragende Forschungsarbeit **mit Bezug zur Energietechnik**

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)):

awards@sps.ch

Einsendeschluss: 31. Januar 2022

Die Preise werden an der Jahrestagung 2022 in Fribourg überreicht. Das Preisreglement befindet sich auf *www.sps.ch*.

Annonce des prix de la SSP pour 2022

En 2022, la SSP attribuera à nouveau des prix de CHF 5000.- chacun, à savoir:

- Le prix SSP offert par l'entreprise *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* 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**
- Le prix SSP offert par l'entreprise *Hitachi Energy Switzerland AG* pour un travail de recherche d'une qualité exceptionnelle **faisant référence au domaine des technologies énergétiques**

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

Délai: 31 janvier 2022

Les prix seront attribués à la réunion annuelle commune qui se tiendra en 2022 à Fribourg. Le règlement des prix se trouve sur les pages web de la SSP: *www.sps.ch*

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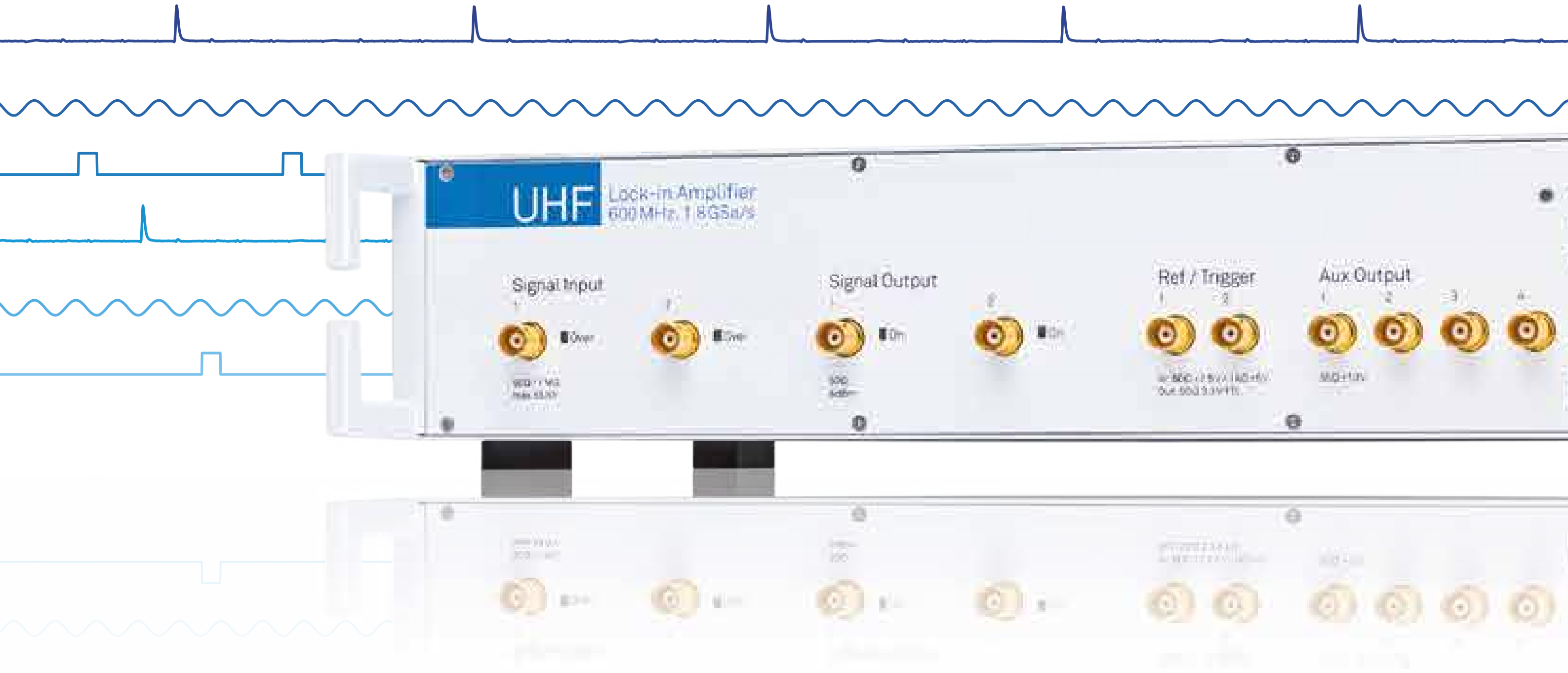

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