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SPG Mitteilungen
Communications de la SSP

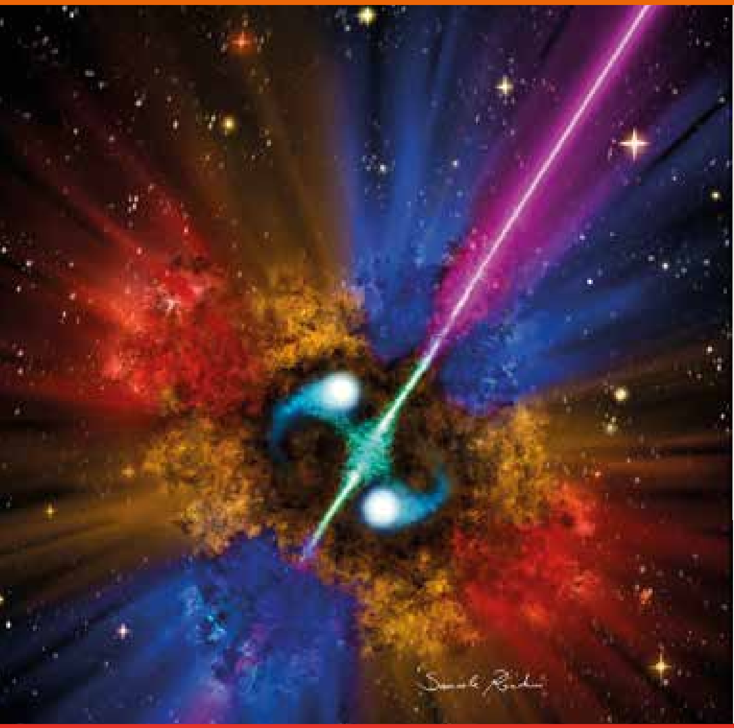
Joint Annual Meeting of the
Swiss Physical Society
Austrian Physical Society
4 - 8 September 2023, Universität Basel

in collaboration with

CHIPP, NCCR SPIN, SGN, Departement Physik - Universität Basel

Call for Abstracts: Submission Deadline 1 May 2023

More information on page 4.



Artistic view of a binary star merger event forming a GRB. Read more on p. 22.

Credit: Samuele Ronchini, GSSI Institute, L'Aquila, Italia

*The **Pascaline** (around 1650), a mechanical calculator, is one of the many achievements of **Blaise Pascal**, whose 400th birthday will be commemorated in a special symposium during our Joint Annual Meeting. See p. 7.*

Mathematisch-Physikalischer Salon, Inv.-Nr. A II 11, Picture: Hans-Peter Klut / Elke Estel © Staatliche Kunstsammlungen Dresden

Inhalt - Contenu - Contents

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satw it's all about technology

Editorial

Symmetric knowledge transfer between research and applications

Bernhard Braunecker, Johan Chang, Ulrich Claessen (SATW Industrial Advisory Board)

The interaction between physics and industry is an important theme that the Swiss Physical Society can further develop in 2023. The recently published ***SPS Focus 2*** [1] highlighted how knowledge transfer from research to industry is well established in Switzerland but also that more physics know-how can be moved from universities to companies, mainly to SMEs. This should allow SMEs to apply novel technologies in their instruments or services based on new materials, quantum phenomena, especially photonics, sensors, modeling concepts etc. Knowledge transfer flows best when organizational layers of a society are aligned. In the context of physics and industry, tighter collaborations between SPS and SATW would be beneficial.

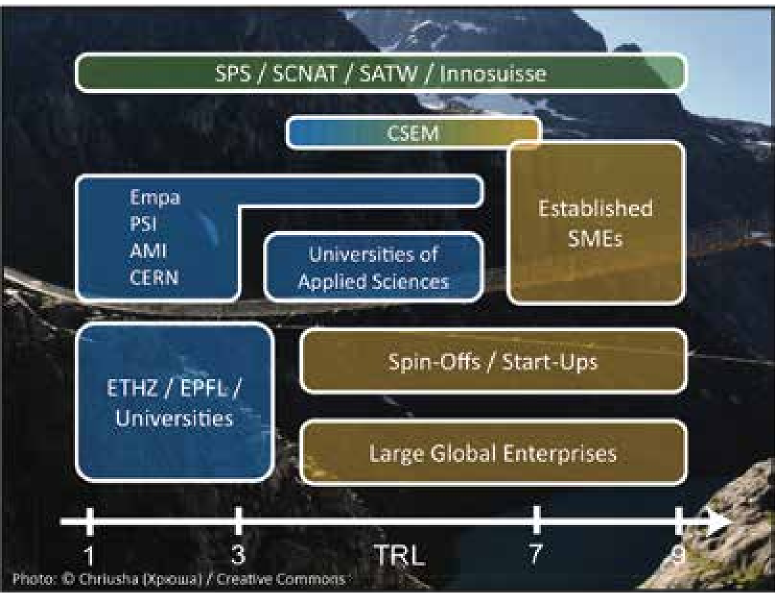


Photo: © Chriusha (Хрюша) / Creative Commons

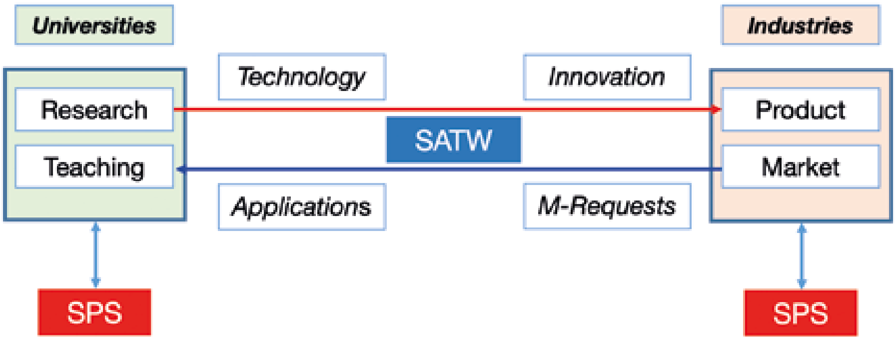
Within the Swiss academies, SATW has the role to scan and evaluate technologies with a Technology Readiness Level TRL between 4 and 7 [2]. This is successfully done by the scientific advisory board WBR, which summarizes its findings every two year in a *Technology Outlook* report with respect to national economic importance and existing national competence. The SATW industrial advisory board IBR - recently revived after years of de facto non-existence - is staffed with representatives from major industries as well as small and medium enterprises. The experience of the IBR members allows to analyse the recommended technologies from WBR according to additional system readiness levels [3].

This analysis includes three pillars:

- IRL (Integration/Interface), asking if the technology can already be combined with other technologies for special application cases?
- MRL (Manufacturing), testing, if the technology can already be taken over by product and process engineers, or must be further developed by R & D physicists and engineers?
- BRL (Business/Investor), which covers all the questions concerning marketing & sales organizations, funding, customer development issues, and many more.

While the knowledge about innovations, i.e. the flow from research to industry, is essential, it is as important to inform the academic institutions about applications. Expectations about market opportunities and requests would, for example, allow the universities to structure their teaching programs in such a way that the students after graduation are best prepared to find attractive jobs in industry. Furthermore, all the start-up companies founded by university graduates would benefit from knowledge of emerging market opportunities to optimize their business model accordingly.

In analogy to the four readiness indices, which completely describe the technical maturing of research ideas into product applications, at least one similar indicator is needed for the knowledge transfer in the opposite direction. This could be a *Selling and Market Readiness Level* SRL, describing not only the selling potential of the innovation, but also whether the company's sales structures are already reorganized and also trained to sensitize key customers accordingly. Such a reorganization is risky, expensive and a readiness index surely helpful.



The bidirectional knowledge flow is ideally symmetric, however with a non-ignorable difference: while universities are open to present their research results, it is much more difficult to draw relevant information about market and application cases from industry. Here personal relations and networks provided by the academies are extremely helpful to close the loop. Closer future collaboration between the SPS and SATW would certainly benefit symmetrical knowledge transfer.

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[1] https://www.sps.ch/artikel/sps-focus/sps-focus-2

[2] https://de.wikipedia.org/wiki/Technology_Readiness_Level

[3] Sean Ross, Bruce Cahan and Ethan Strijbosch, https://urbanlogic.org/readiness-levels-drive-innovation/ ; Optics and Photonics News, September 2022, p. 24-7

Joint Annual Meeting of SPS and ÖPG
Basel, 4 - 8 September 2023

The next annual meeting, as every two years jointly with our colleagues from the *Austrian Physical Society*, will take place from 4 - 8 September 2023 at the "Kollegienhaus" of the Universität Basel.

The conference will open this year on Monday, 4 September, in the afternoon with a symposium acknowledging the ***400th Birthday of Blaise Pascal*** (see p. 7). Also on Monday, the satellite event ***Women in Physics Career Symposium***, after last year's successful launch, will have its second edition (see p. 7).

From Tuesday to Friday, ten renowned speakers will address latest advancements in different research fields in the plenary session, while the parallel sessions will allow in-depth discussions in several topical fields. A poster exhibition on Tuesday and Wednesday will complement the scientific program.

The *Swiss Institute for Particle Physics* (CHIPP), the *Swiss Neutron Science Society* (SGN) and the *NCCR SPIN* will also contribute to the program. Thanks to all these collaborations, our joint annual meeting will offer again an exciting program, covering latest advancements of physics in a wide range of fields at its best.

Scientific Program

Plenary Session

- **Louise Harra,** Physikalisch-Meteorologisches Observatorium Davos / World Radiation Center (PMOD / WRC): *A journey to the Sun: why, how and what is being discovered*
- **Felix Mayer,** Sensirion AG, Stäfa: *Sensirion: From start-up to a global player*
- **Karina Morgenstern,** Ruhr-Universität Bochum: *Tailoring the environment to steer laser-driven reactions at surfaces: Solvation, confinement, and more*
- **Peter Puschnig,** Universität Graz: *Photoemission orbital tomography: imaging molecular orbitals at intrinsic length and time scales*
- **Sascha Schmeling,** CERN: *Science Education in an International Context*
- **Anna Sfyrla,** Université de Genève: *Looking forward to new physics with the LHC*
- **Markus Valtiner,** Technische Universität Wien: *High-resolution and operando analysis for understanding surface and interface processes*
- **Bodo Wilts,** Universität Salzburg: *Amorphous photonic networks in insects*
- **Christian Wüthrich,** Université de Genève: *Out of nowhere: The emergence of spacetime in quantum gravity*
- **Anton Zeilinger,** Universität Wien: *Classical and Quantum Information*

Topical Sessions

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

- Applied Physics, Acoustics
- Atomic Physics and Quantum Photonics
- Biophysics, Medical Physics and Soft Matter
- Condensed Matter Physics
- Gravitational Waves
- History and Philosophy of Physics
- Nanotechnology: From Hype to Application
- Neutron Science *
- New prospects in ARPES for quantum materials
- Nuclear, Particle- & Astrophysics **
- Plasma Physics
- Quantum Computing ***
- Spintronics and Magnetism at the Nanoscale
- Surfaces, Interfaces and Thin Films

* in collaboration with the Swiss Neutron Science Society (SGN); ** in collaboation with CHIPP;
*** organised in collaboration with NCCR SPIN

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

Poster Session

The poster session will start on 5 September evening with an apéro and will continue on 6 September with a lunch buffet. **All** posters are presented on both session days.

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

The maximum poster size is A0 (portrait).

General Assembly

The general assembly is scheduled for 4 September in the afternoon. The agenda will be published in the next issue of the *SPG Mitteilungen*. We encourage all members to actively participate and contact the committee if special points of interest should be discussed at the assembly.

Award Ceremony

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

The ÖPG will also award their various winners. Furthermore the winners of the Charpak-Ritz award, the SGN award and the CHIPP award will also be honored.

The award ceremony will be held on 5 September at 11:00h.

Conference Dinner

A conference dinner is scheduled for the evening of 7 September. Information on the location and more details will be available on our web site soon.

Vendors Exhibition

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

Abstract Submission

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

The submission of abstracts must be done online. Visit our webpage *www.sps.ch* and follow the link to the submission form. Further explanations are available there. The submission form will be activated shortly.
The conference program will be available in July 2023 on *www.sps.ch*. Please check the web regularly for further information and updates.

Submission Deadline: 1 May 2023

Conference Fees, Registration and Payment

The conference fees cover the participation to all sessions, including coffee breaks (all days), poster-apéro (Tuesday) and lunch buffet (Wednesday). The conference dinner on Wednesday evening will be charged separately.

Pay your conference fee in time and save money !

The regular fees, as shown in the table below, hold for payments reaching us before 15 August 2023.

Category:	*CHF*
Individual Members of SPS, ÖPG, CHIPP	150.-
Students before Master/Diploma degree (*)	100.-
Other persons	190.-
Plenary speakers, invited speakers, awardees	0.-
Conference Dinner	90.-

(*) Students licence required

For payments done later than 15 August a surcharge of CHF 20.- will be added. This applies also for participants paying cash at the conference.

For registration just follow the link on *www.sps.ch*. Payment information is available directly during the registration process. Please make sure that your name and the purpose of the payment are indicated.

Attention: Fees are not refundable in case of individual cancellation. In the case the entire conference needs to be cancelled, we will contact participants who have already paid for the refunding process.

Registration Deadline: 15 August 2023

Special offer for non-members:

Do you plan to participate in our meeting and want to become a member of the SPS ? Take advantage of our special offer of CHF 200.- covering the conference fees and the membership for 2023. (CHF 220.- after 15 August) !

Fill out the online-registration form, choose the option "Special offer", then download, fill and sign the admission form for new members, and return it as soon as possible to the SPS Secretariat. The membership admission form is available on
www.sps.ch/fileadmin/doc/Formulare/anmeldeformular_d-f-e.pdf .

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

Additional information for selected sessions

Nanotechnology: From Hype to Application

Nanotechnology was enabled by our ability to see at the nanoscale with novel microscopy techniques, namely scanning electron microscopy and scanning tunneling microscopy. For their invention Ernst Ruska, Gerd Binnig and Heinrich Rohrer were awarded the Nobel prize in Physics 1986. This marked the beginning of huge excitement and significant hype both in research and industry, raising high expectations for ubiquitous nanotechnology applications.
In this year's ***Physics in Industry*** session, we want to bring together presentations from a broad range of companies that have managed to persevere beyond the initial hype and are applying nanotechnology today.
If you are interested in presenting a talk in this session please contact the section heads.

Contact: Thilo Stöferle (tof@zurich.ibm.com), Andreas Fuhrer (afu@zurich.ibm.com), Peter Korczak (peter.korczak@aon.at), Christian Teissl (christian.teissl@destination-wattens.at)

Theoretical Physics

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

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

Gravitational Waves

For this special session contributions covering all aspects of gravitational wave physics are welcome, in particular those connected with the Einstein Telescope (ET), the LISA mission, and the ongoing LIGO-Virgo detectors.
Relevant topics include data analysis, theoretical aspects, and experimental challenges of ET and / or LISA.
We particularly encourage PhD students and postdocs to submit abstracts and to join the meeting. Depending on the number of proposed contributions, the session will take place on one or two afternoons. Poster contributions are also welcome.

Contact: Steven Schramm (steven.schramm@cern.ch), Philippe Jetzer (jetzer@physik.uzh.ch)

Quantum Computing (by NCCR SPIN)

The quantum computing session will combine presentations on recent scientific advances in the field of quantum computing with various qubit platforms. Contributions from ion traps, neutral atoms, superconducting qubits, spin qubits and other hardware platforms are welcome, as well as presentations that address progress on scalable qubit control, error correction, novel quantum algorithms and software applications. Both Austria and Switzerland are important players in this thriving area of research with many groups contributing to European and other important international research programs. The session is organized by the NCCR SPIN: Spin qubits in Silicon (https://nccr-spin.ch/), and wishes to bring together the quantum computing communities from Austria and Switzerland. We welcome oral and poster contributions from both senior and junior researchers.

Contact: sps-qc@nccr-spin.ch

History and Philosophy of Physics

Our session is open to any topic in the history and philosophy of physics. A special focus will be on astronomy, astrophysics and cosmology. Since ancient times, the study of the sky has fascinated human beings. In the last few decades, astrophysics and cosmology have seen spectacular breakthroughs, e.g. the discovery of exoplanets or the confirmation that the expansion of the Universe is accelerated. We thus invite contributions that consider astronomy, astrophysics and cosmology from a historical or philosophical perspective.

Contact: Claus Beisbart (Claus.Beisbart@unibe.ch), Bruno Besser (Bruno.Besser@oeaw.ac.at)

Condensed Matter (KOND)

The condensed matter program welcomes contributions from all topics within Condensed Matter Physics, including magnetism, superconductivity, semiconductors and more. Investigations by advanced experimental techniques, e.g. by using synchrotron radiation, are highly welcome. Where relevant, we encourage participants to submit their abstracts to the respective focus sessions described below.

Contact: Henrik M. Rønnow (henrik.ronnow@epfl.ch), Ilaria Zardo (ilaria.zardo@unibas.ch), Alberta Bonanni (alberta.bonanni@jku.at), Roland Resel (roland.resel@tugraz.at)

New prospects in ARPES for quantum materials

Angle-resolved photoemission spectroscopy (ARPES) is one of the most powerful techniques to measure the momentum-resolved electronic structure of materials. In the recent years, the development of high brilliance synchrotron facilities, as well as stable laser technology, have allowed new possibilities like micro- and nano-ARPES, in-operando ARPES on tiny devices, as well as versatile time-resolved ARPES, to cite a few of them.
This special session is dedicated to review the recent ARPES developments and highlight the most advanced achievements in systems ranging from quantum materials, correlated systems and complex devices. The session will bring together the ARPES research groups and serve to elaborate novel perspectives and collaborative development.

Contact: Claude Monney (claude.monney@unifr.ch), Luc Patthey (luc.patthey@psi.ch)

Neutron Science

Neutrons produced at large-scale research facilities provide key insights in topics ranging from particle to solid state physics, to quantum materials, to soft matter, to functional and engineering materials. Together with our colleagues from the section *Physics with Neutron and Synchrotron Radiation* (NESY) within the Austrian Physical Society, the *Swiss Neutron Science Society* welcomes abstract submissions from all topics where neutron experiments have contributed, or may contribute in the future.

Contact: Roland Resel (roland.resel@tugraz.at) and Marc Janoschek (marc.janoschek@psi.ch)

Spintronics and Magnetism at the Nanoscale

This focus session concerns the latest advancements in the fabrication, measurement, and exploitation of novel functionalities in spintronic and nanomagnetic materials. We aim to showcase recent work conducted by experimentalists and theorists from Switzerland, Austria, and neighboring countries who are researching the magnetic properties of thin films, interfaces, and nanostructures. Hans Hug (Empa) and Santa Pile (JKU Linz) will present invited talks during this session.

Contact: Jeffrey Brock (jeffrey.brock@psi.ch), Aleksandr Kurenkov (aleksandr.kurenkov@psi.ch), Laura Heyderman (laura.heyderman@psi.ch)

Symposium: 400th Birthday of Blaise Pascal

This year marks the 400th birthday of Blaise Pascal (1623 - 1662). Over the course of his short life, Pascal made significant contributions not only to philosophy, but also to several fields of the natural sciences, such as mathematics, the technology of early calculating machines, and especially physics, where he verified Torricelli's theory of atmospheric pressure by careful experiments. It is interesting to recall his critical reflections on what we might call ‘artificial intelligence‘: “*The arithmetical machine produces effects which approach nearer to thought than all the actions of animals. But it does nothing which would enable us to attribute will to it, as to the animals.*" (Les Pensées, Frg. 340, https://sourcebooks.fordham.edu/mod/1660pascal-pensees.asp).

The SPS and the ÖPG, in partnership with the French Physical Society (SFP), take the occasion of the anniversary to organize a mini-symposium on Pascal as part of their joint annual meeting in Basel. As in 2021 in Innsbruck, when the 450th anniversary of Johannes Kepler's birth was commemorated, four lectures addressing the history and the impact of Pascal's work up to our time will be given.

- **Dominique Descotes,** Université Clermont Auvergne:
  Order and disorder in Pascal’s Pensées
- **Helena van Swygenhoven,** Paul Scherrer Institut Villigen:
  The unit Pascal in material science and engineering
- **Michael Korey,** Staatliche Kunstsammlungen Dresden, Mathematisch-Physikalischer Salon:
  Mechanical Thinking: The Pascaline and its Planetary Predecessors
- **Thomas Schulthess,** ETH Zürich & Swiss National Supercomputing Center (CSCS) Lugano:
  From Pascaline to Piz Daint in the Alps infrastructure: a modern day view of computing in science

This symposium is free of charge, no registration needed.

Satellite Event: Women in Physics Career Symposium

Following the success of last year’s inaugural Women in Physics Career Symposium, SPS has decided to turn this event into a sustainable series with the aim of boosting the careers of women physicists. Our focus is on building a professional and mentoring network in physics for female early-career scientists in the undergraduate up to postdoctoral stages. Like last year, the event will feature a series of career talks, which will provide information on navigating a career in physics from the personal perspective of invited speakers covering several career levels. This year, speakers pursuing successful careers both in and outside academia will provide us with insights about key moments of their careers. The career talks will be complemented by a podium discussion, in which participants can ask questions and share experiences, advice, and ideas. In addition, ample opportunities for networking, exchange of experiences and ideas will be provided via extended coffee breaks, lunch, and a dinner.

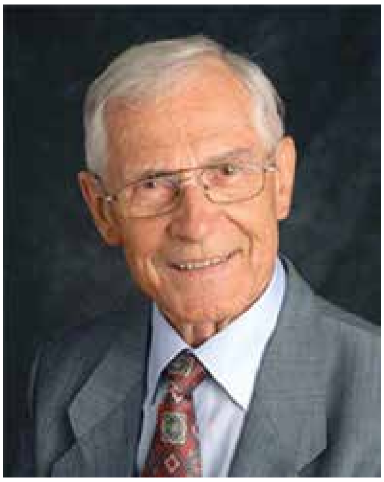
Although, the event is focused on connecting mentees from the undergraduate up to postdoctoral career level with experienced mentors, we invite female participants from all career levels to register for this event to contribute and benefit from the networking. In addition, we are asking interested colleagues willing to act as mentors to register (a list of last year’s mentors can be found here: https://www.sps.ch/en/events/sps-annual-meeting-2022/satellite-event-women-in-physics-career-symposium/mentors), where we also encourage male colleagues to contribute.

The event is sponsored by the University of Zürich, the Paul Scherrer Institute, the Swiss Academy of Sciences (SCNAT) and SPS. Further contributions are most welcome. More details will be made available soon.

Contact: Zeljka Budrovic (zeljka.budrovic@psi.ch), Lea Caminada (lea.caminada@psi.ch), Ellen Fogh (ellen.fogh@epfl.ch), Marc Janoschek (marc.janoschek@psi.ch), Christine Klauser (christine.klauser@psi.ch), Hubertus Luetkens (hubertus.luetkens@psi.ch), Teresa Montaruli (Teresa.Montaruli@unige.ch), Katharina Müller (kmueller@physik.uzh.ch), Philipp Schmidt-Wellenburg (philipp.schmidt-wellenburg@psi.ch), Anna Sfyrla (Anna.Sfyrla@unige.ch)

In Memoriam Peter K. F. Grieder

Peter Karl Ferdinand Grieder, renowned for his fundamental contributions to high-energy cosmic ray research and neutrino astronomy, died on 14 October 2022 in Bern, at the age of 94. After a rich life dedicated to science, he has been released from cancer. We mourn the loss of a good colleague and dear friend.



Peter was born in Langenthal, Switzerland, on 22 November 1928. After school, he first made an apprenticeship as a radio technician. He then graduated as an electrical engineer at the Burgdorf campus of the Bern University of Applied Sciences and worked in industry in the field of television development for almost two years. In 1953 he went to the USA to further his skills in the domains of electronics and microwaves. In Chicago, he worked for Admiral Corp. where he was involved in colour television research. At the same time, he was registered as a student at the Graduate School of the Illinois Institute of Technology (IIT), with the aim to obtain a Master's Degree in electronics. However, at this point his interests shifted more and more towards physics. In 1957, he obtained his MS degree in Physics from the IIT. For his thesis, he did research with the Argonne group of the U.S. Atomic Energy Commission at the University of Chicago. There he came also in contact for the first time with cosmic ray physics, taking part in seminars of Professors Simpson, Schein and Chandrasekhar. However, he had to abandon a continuation of his career in Chicago because he as a Green Card holder was facing problems with the U.S. military. He returned to Switzerland in 1959.

In 1961 Peter got his PhD from the University of Bern, where he did research under Prof. F. G. Houtermans in high-energy cosmic ray physics. He then worked successively as a postdoctoral scientist at the Niels Bohr Institute in Copenhagen with Prof. B. Peters on quark hunt experiments, at CERN in Geneva in the experimental and later on in the theoretical physics division with Drs. R. Hagedorn and M. Jacob on models of high energy hadronic interactions and multiparticle production, in conjunction with air showers, and he was a visiting professor at the Institute for Nuclear Studies of the University of Tokyo. In 1971, he habilitated, and in 1978, he was appointed Professor of Physics at the University of Bern. He was a guest professor for many years at the University of Hawaii. He also served the national and international science community, e.g. by organizing conferences, and he acted as secretary of the Swiss Physical Society from 1985 to 1987. Since 1994 he was Prof. emeritus, but continued scientific activity in High Energy Cosmic Ray Research and Neutrino Astronomy at the Physics Institute of the University of Bern.

Peter's work was always at the forefront of the field. He was among the first to introduce the computer simulation technique into the study of air showers. He developed the ASICO air shower simulation program system which later became the foundation of the widely used Karlsruhe Extensive Air Shower Simulation Code CORSIKA. Later, together with Prof. J. G. Learned from the University of Hawaii, USA, and with Prof. F. Reines, Nobel Laureate, as well as with colleagues from other institutions, he was co-initiator of the pioneering DUMAND neutrino telescope project in Hawaii. This project for the search of high energy neutrinos from active galactic nuclei opened a new window in astrophysics and was the template for all presently existing and planned giant neutrino telescopes, like e.g. IceCube in Antarctica.

Peter was a hardworking, multi-skilled, and open-minded person. His enthusiastic nature and never flagging work energy, his phenomenal memory and his global network of relationships were as impressive as his striving for perfectionism. He loved exchanging ideas with colleagues, be it as an interested listener at lectures at the University or as an active participant of conferences. His long-term collection of proceedings brought back from the International Cosmic Ray Conferences ICRC is probably the most comprehensive individual one worldwide. Thanks to his outstanding experimental and theoretical work, Peter has gained worldwide recognition and respect, as documented e.g. by the honorable mention by Prof. S. K. Gupta, the then Chairman of the IUPAP C4 Commission, during the closing session of the 2021 ICRC. Besides his intense scientific work, he, together with his wife Estelle, maintained an active social life. Both loved traveling, and the regular skiing holidays in Zermatt were an integral part of their annual program.

Peter has written remarkable books on cosmic ray physics, which transmit the enthusiasm he had for this amazing field where experiments are adventures in the most amazing places in the world. His interest was initiated by the DUMAND enterprise, the installation of the first string of photosensors in the deep sea of Big Island in Hawaii waters. His latest enterprise captures the fascinating field of multi-messenger astronomy, where new messengers enter into play to reinforce the impact of photon astronomy. He pedagogically leads the reader into the wonder of neutrino astrophysics and gravitational waves from their concepts to their amazing results. The book is in completion by Prof. Teresa Montaruli who witnessed the last year of efforts on this by Peter, leading to any sort of fight against the decease that took him away from his beloved and deep passion for scientific culture.

Peter is survived by his wife Estelle, his daughter Marina and his son Ralph and their families with two and three grandchildren respectively. Our deepest sympathy and sincere condolences go to all of them.

Erwin O. Flückiger and Teresa Montaruli

(using many of Peter's own words: www.space.unibe.ch/about_us/personen/prof_em_dr_grieder_peter/index_eng.html)

The Laureates of the Nobel Prize in Physics 2022

The Nobel Prize in Physics 2022 was awarded to **Alain Aspect** (France), **John F. Clauser** (USA) and **Anton Zeilinger** (Austria) ***"on the grounds of experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"***. The results of their work paved the way for new technologies based on quantum information.

"Have you heard of Aspects' experiments?" This question was one of the first asked by my new fellow students after I moved from Toulouse to Orsay university in September 1982. Leaving my native town was then motivated to prepare myself to follow master courses of theoretical physics in Paris. At that time I had been aware of the Einstein-Podolsky-Rosen (EPR) paradox and still remember my proudness when I learnt that an experimentalist working at the Institut d'Optique d'Orsay succeeded in clearing it up.

Beyond the Einstein-Bohr debate on the completeness of quantum physics theory, the EPR paradox raised the fundamental question of our perception of reality. The "classical" concept of reality postulated that the state of a single particle (e.g., a photon) having interacted in the past with a second one could be measured *independently* of the latter over long enough separation distances. John Clauser, Alain Aspect and Anton Zeilinger experimentally showed that this property does not hold. Their successive demonstrations took many years of incredible efforts to dispose of the suitable lasers producing appropriate photon pairs and to build up the right setups overcoming the major loopholes inherent to the EPR "gedanken experiment". This impressive work led to award them with the 2022 Nobel prize in physics for proving the violation of Bell inequalities – thereby ruling out the existence of hidden variables by which two particles may remain "classically" connected to each other – and for pioneering practical applications of such "entangled" states in quantum information science.

The following articles, written by former collaborators of the Nobel laureates, nicely relate this heroic period in the recent history of science and further developments opening the fields of Bose-Einstein condensates, quantum teleportation and quantum computing.

The selection committee of the 2022 Nobel prize in physics recognized the soundness of the non-separability principle, indicating that nature should be non-local. Despite this seminal discovery we are, however, still missing a robust theoretical description of non-locality. The philosophical debate launched a century ago by Einstein and Bohr is thus not closed yet and goes on arousing numerous vocations in fundamental physics.

Luc Bergé, President of the European Physical Society

Some personal memories

Reinhold A. Bertlmann, Faculty of Physics, University of Vienna, Boltzmanngasse 5, 1090 Vienna, Austria

This Nobel Prize is a huge triumph for a field that was once so stigmatized.

Prologue

It is hard for young physicists today to imagine just how frowned upon it once was to discuss questions related to the foundations of quantum mechanics. The debates in the 1930s between the great old men, Einstein and Bohr, were considered to be purely philosophical and as having no influence on actual physics. We were told that Bohr was right and Einstein was wrong. David Mermin once coined the phrase "*Shut up and calculate!*" to summarize the Copenhagen-type views of that time.

In particular, the significance of the Einstein-Podolsky-Rosen (EPR) Gedanken-Experiment of 1935 [1] was not recognized at all. It was considered to be of no use and was entirely disregarded for about 30 years. I remember that in the early 1980s Abraham Pais, a distinguished physicist from Rockefeller University who had just published the bestseller "*Subtle is the Lord: The Science and the Life of Albert Einstein*" [2], told me: "*The EPR paper was the only slip Einstein made!*" How very wrong some judgements and prophecies within the field of physics can be!

In 1964, when John Bell was on sabbatical in the US, he had the leisure to reconsider the EPR case and he wrote the paper "*On the Einstein-Podolsky-Rosen Paradox*" [3], which contained Bell's inequality. A Bell inequality, quite generally, is an inequality between expectation values of joint measurements of two parties, customarily called Alice and Bob, which all local realistic theories have to fulfil but is violated by quantum mechanics. We also speak of *Bell's Theorem*, realized via Bell inequalities: "*Local realistic theories are incompatible with quantum mechanics.*" However, for a long time, Bell's work did not arouse any interest.

John Clauser

The first person to become interested in the subject was John Clauser, a young postdoc from Columbia University, in the late 1960s. When he studied Bell's inequality paper he saw that it contained a bound for all hidden variable theories – which he believed in – and he was fascinated and wanted to show evidence for it. So he planned to perform the experiment.

However, the value of experiments of this type was not recognized at that time. When Clauser had an appointment with Richard Feynman at Caltech to discuss an experimental EPR configuration for testing the predictions of quantum mechanics, Feynman immediately threw him out of his office, saying [4,5]:

> *“Well, when you have found an error in quantum-theory's experimental predictions, come back then, and we can discuss your problem with it.”*

Fortunately, Clauser remained resolute and was determined to complete the experiment. He wrote letters to David Bohm, Louis de Broglie and John Bell – all were declared realists – seeking advice or moral support. Let’s quote Bell’s reply [4]:

> *“In view of the general success of quantum mechanics it is very hard for me to doubt the outcome of such experiments. However, I would prefer these experiments, ... , to have been done ... Moreover, there is always the slim chance of an unexpected result, which would shake the world!”*

Belonging to the rebellious Hippie generation of the 1960s [6], Clauser certainly “*wanted to shake the world*” [5], and in 1969 he sent an abstract to the Spring Meeting of the American Physical Society proposing the experiment. Soon afterwards, Abner Shimony called him and told him that he and his student Michael Horne had had very similar ideas. So they joined forces, and together with Richard Holt, a PhD student working with Francis Pipkin from Harvard, they wrote the famous CHSH paper [7], in which they proposed an inequality that was well adapted to experiments.

Clauser finally carried out the experiment in 1972, together with Stuart Freedman [8], a graduate student at Berkeley who received his PhD for this experiment. As pointed out in the CHSH paper [7], pairs of photons emitted in an atomic radiative cascade would be suitable for a Bell inequality test. Clauser and Freedman chose calcium atoms pumped by lasers, where the excited atoms emitted the desired photon pairs. The signals were very weak at that time, a measurement lasted for about 200 hours. For comparison with theory a very practical inequality was used, which was derived by Freedman [9]. The outcome of the experiment is well known: they obtained a clear violation of the Bell inequality very much in accordance with QM. This result was confirmed by subsequent experiments [10, 11].

Performing this experiment was truly a heroic act at that time; everything was self-made, not only the laser but also all the remaining equipment. Furthermore, Clauser could only work on the experiment because Charles H. Townes was intrigued by Clauser’s ideas and offered him a job, half for Clauser’s project and the other half for Townes’ radio astronomy. Regrettably, because of this experiment, Clauser was not able to pursue an academic career. But it can be seen as redemption that he has now been awarded the Nobel Prize.

Alain Aspect

Alain Aspect, a young French physicist, was so impressed by Bell's inequality paper that he immediately decided to focus his Thèse d'Etat on this fascinating topic. He visited John Bell at CERN to discuss his proposal. John's first question to him was, as Alain later told me, “*Do you have a permanent position?*” Bell was so scared that it would ruin Aspect’s career. Only after Aspect's answer in the affirmative could the discussion begin. Aspect's goal was to include variable analyzers in the setup. In the early 1980s Aspect and his collaborators performed a whole series of experiments [12, 13, 14], with the result that the Bell inequalities used were significantly violated in each experiment. It was this that has now been recognised with the awarding of the Nobel Prize. An appreciation of Aspect’s work can be found in a separate article.

Anton Zeilinger

In the 1990s, after Aspect’s experiments, the physics community began to notice the importance and impact of such Bell-type experiments. Quantum information, communication and computation, centred around Bell inequalities and quantum entanglement, were gaining increasing interest. Now at last the prevailing attitude towards the foundations of quantum mechanics was changing. At the same time, the technical capabilities, the electronics and the lasers, were also improving considerably. Most important was the invention of a new source for creating two entangled photons, namely spontaneous parametric down conversion. Here a nonlinear crystal was pumped with a laser and the pump photon was converted into two photons that propagated on two different cones. On one cone the photons were vertically polarized and on the other horizontally. In the overlap region they were entangled. Such an EPR source was used by Anton Zeilinger and his group when they performed their celebrated experiments. But let me describe everything in order.

First of all, writing about Anton Zeilinger is a quite complex task. His accomplishments are substantial and influential in so many areas, not only in quantum physics and quantum information but also in teaching and in science administration. Zeilinger contributed to the popularisation of science – he is known by the public as “*Mister Beam*”. All of this, alongside his love for philosophy and art, makes Zeilinger an incarnation of a Renaissance Scholar. So I can only focus here on just some of his achievements.

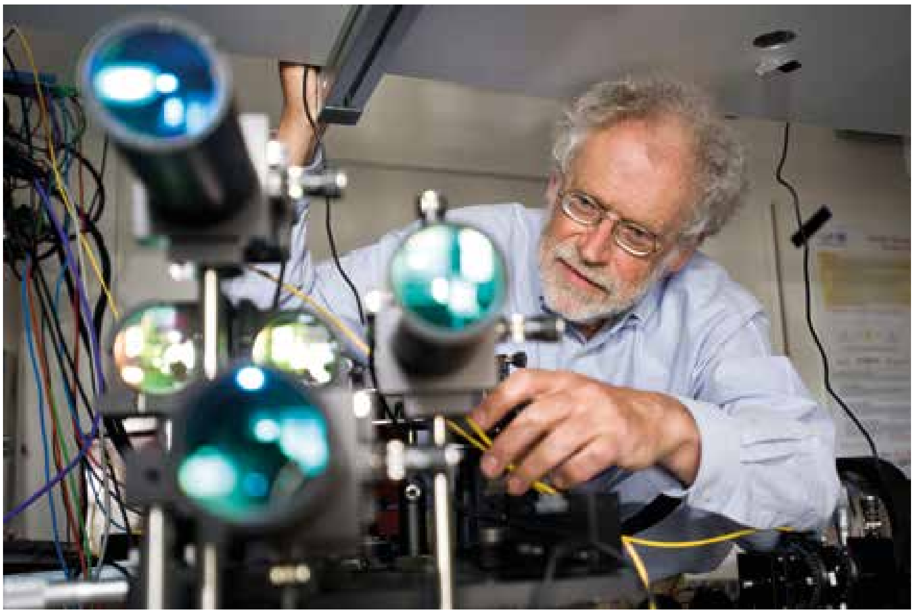
Zeilinger’s interest in physics was always driven by curiosity. Even in experiments that have made applications possible, his interest has been rooted in curiosity. Also notable is the courage he showed when, in around 1990, he switched from neutron to photon physics when he became a professor at the University of Innsbruck. This was, of course, not without considerable risk. But thanks to his unerring intuition in physics and also his charisma, Zeilinger gathered highly talented students around him with whom he performed fascinating experiments.

I first met Zeilinger in person in 1991 at the Cesena Conference [15]. We immediately found common interests and decided to work together. One of our aims was to educate the new generation of young physics students on the topic of Bell-like experiments.

In 1994 we established a course titled “*Foundations of Quantum Mechanics*” at the University of Vienna. Initially it took place in a small barrack in the old AKH (Allgemeines Krankenhaus - Vienna’s former general hospital, now a campus of the University of Vienna) next to the so-called Narrenturm (fools tower), a notorious place. Anton and his group would visit from Innsbruck four times per semester. The students were required to jointly deliver a talk, supplemented by a handout that would be distributed beforehand. There was always a break midway through the session, when coffee and homemade cakes would be served. It was in this cosy atmosphere that the Viennese students animatedly discussed the newest experiments being performed in Innsbruck.

Experiments which have since become famous were reported there first-hand, for example: Dik Bouwmeester, a member of Zeilinger's group, reported on "*Experimental quantum teleportation*" [16], and Gregor Weihs explained the Bell-type experiment "*Violation of Bell's Inequality under Strict Einstein Locality Conditions*" [17].

As you can imagine, the course became highly popular among the students and it continued running for about 25 years. It was undoubtedly one of the most influential courses at the Faculty of Physics in Vienna.



Anton Zeilinger in his laboratory. Picture © Jacqueline Godany, IQOQI Vienna

In 1999 Zeilinger and his whole team relocated from Innsbruck to the University of Vienna, where he became Professor of Experimental Physics. His debut was the famous experiment "*Wave-particle duality of C_{60} molecules*", which demonstrated the quantum mechanical interference effects by using big molecules such as fullerenes [18]. It opened up a new field of research, led by Markus Arndt, into interfering even much bigger molecules.

Next followed the "*Experimental test of quantum nonlocality in three-photon Greenberger–Horne–Zeilinger entanglement*" [19]. Back in 1989 Zeilinger had collaborated with Daniel Greenberger and Michael Horne (GHZ) and they had written one of the most influential papers in the field [20], commonly called the *GHZ Theorem*.

It was David Mermin, fascinated by this issue of non-local quantum correlations, who turned the original GHZ discussion into a gedanken experiment for a system consisting of three spin-1/2 particles. In his famous Physics Today article Mermin [20] gave an extremely clear and most comprehensible presentation of the GHZ argument, which still makes it appealing to the physics community nowadays. John Bell too, who had received a copy from Mermin, replied "*I am full of admiration for your 3-spin trick*" (private communication [20]).

The GHZ Theorem à la Mermin asserts:

> *"For a three spin-1/2 system there exists a physical situation where all local realistic theories are inconsistent and incompatible with quantum mechanics."*

It is much more restrictive than Bell's Theorem which needs expectation values, i.e., the statistics of events. These three-particle entangled states, GHZ states, opened up the entanglement research for higher multi-particle states which are important for quantum computation.

Entanglement swapping is another amazing quantum feature which Anton and his colleagues had already discovered back in 1993 [21]. It is actually the teleportation of an entangled state. More precisely, given two pairs of entangled photons, when performing a Bell state measurement for two photons of each pair, it instantaneously brings the remaining two photons into the same entangled Bell state. It was experimentally realized by Zeilinger's group in 1998 [22].

Even more amazing is the delayed-choice of entanglement swapping, where the order of the measurements is reversed as compared to standard entanglement swapping [23]. Here I became involved in Anton's activities as well and together with Walter Thirring and Heide Narhofer we were able to demonstrate that this phenomenon can be traced back to the commutativity of the projection operators of the measurements [24].

Before I continue to describe Zeilinger's experiments, I would like to mention that I also had the pleasure to collaborate with Anton on some other memorable events. In 2000, right after Zeilinger and his team had settled in Vienna, we organized a conference in honour of John Bell: "*Quantum [Un]Speakables I*" [25]. There we had numerous notable speakers, among them, just to mention a few: Mary Bell (the widow of John Bell), Gerard 't Hooft, Jack Steinberger, Roger Penrose, Alain Aspect, John Clauser, Anton Zeilinger (6 Nobel Prize winners so far), Roman Jackiw, David Mermin, Simon Kochen, Abner Shimony, Michael Horne, Daniel Greenberger, Nicolas Gisin, Helmut Rauch and others. In 2014 we organized a follow-up conference, "*Quantum [Un] Speakables II*" [26], where we had similarly distinguished speakers.

In the late 1990s there was an increasing amount of activity to test Bell inequalities. A record was set by Nicolas Gisin's group [27] in Geneva by using energy-time entangled photon pairs in optical fibers. They succeeded in separating their observers Alice and Bob by more than 10 km and could show that this distance had practically no effect on the entanglement of the photons.

In the new millennium a whole series of experiments was carried out, mainly testing the entanglement of particles at long distances via Bell inequalities. The vision was to be able, ultimately, to install a global network in outer space.

By further pushing at the limits of distance, Zeilinger's group set a record with an open-air Bell experiment over 144 km between the two Canary Islands, La Palma and Tenerife [28]. Zeilinger's former student Jian-Wei Pan and his group later extended the limit to 1120 km [29].

Up until 2015 the three loopholes: "*Locality, freedom-of-choice and fair sampling*" had only been closed separately in photon experiments. But Zeilinger's group succeeded in closing all three loopholes in one single experiment [30] (two other groups also achieved this, one in Boulder, the other one in Delft). Technically it was very challenging.

Furthermore, in 2018, an impressive "*Cosmic Bell test using random measurement settings from high-redshift quasars*" [31], whose light was emitted billions of years ago, was carried out by Zeilinger's group. This experiment pushes back to at least 7.8 Gyr ago, the most recent time by which any local-realist influences could have exploited the "freedom-of-choice" loophole to account for the observed Bell violation. Any such mechanism is practically excluded, extending from the big bang to today.

In collaboration with the Chinese Academy of Sciences, and in particular with the group of Jian-Wei Pan, Zeilinger and his team implemented quantum communication protocols between the satellite "*Micius*" and receiving stations on earth. The goal was to demonstrate a secure quantum key distribution. This key was used for the first intercontinental video call encrypted via quantum methods and demonstrated that a tap-proof quantum internet is possible.

Zeilinger also made fundamental contributions as a theorist and philosopher. Together with his student Časlav Brukner he developed a completely novel view of the meaning of a quantum state. According to their view, the quantum state represents "*information about possible future experimental outcomes*" [32,33]. Information is the most fundamental concept in quantum physics. The physical description of a system is nothing but a set of propositions together with their truth values, "*true*" or "*false*". Amazingly, relying on a few information-theoretical assumptions, they were able to derive the characteristic features of quantum mechanics such as: coherence–interference, complementarity, randomness, the von Neumann evolution equation, and, most importantly, entanglement.

Discussion between Reinhold Bertlmann, Anton Zeilinger and Walter Thirring on the topic "Zufall ist, wo Gott inkognito agiert" (2013). Photo © Mirjam Reither

I was also able to share in Zeilinger's philosophical and religious view of the world in a discussion between Anton, Walter Thirring and myself, as shown in the photo. The discussion, titled "*Zufall ist, wo Gott inkognito agiert*" (*Randomness is where God acts incognito*), was led by Thomas Kramar, a science journalist, and appeared in the Austrian newspaper "*Die Presse*" (23.3.2013).

Zeilinger also attracted many highly talented students who went on to become distinguished professors in their own right, reminiscent of Bohr and his group in the old days. Weihs, Arndt, Brukner and Pan I have already mentioned, some others are: Thomas Jennewein, with whom Zeilinger performed quantum cryptography experiments [34], or Phillip Walther, with whom he investigated quantum computing [35]. In the middle of the 2000s he began working with Markus Aspelmeyer on the cooling of mechanical resonators by radiation pressure [36], a new field of research now led by Aspelmeyer.

Zeilinger has held several important positions within the science administration. For instance, he became Dean of the Faculty of Physics at the University of Vienna (2006 – 2009), an important step which enabled the implementation of a reform to the law concerning the organization of Austrian universities, which he also helped to shape. Furthermore, Zeilinger was director of the Institute for Quantum Optics and Quantum Information (2004 – 2013), and he became President of the Austrian Physical Society (1997 – 1998) and President of the Austrian Academy of Sciences (2013 – 2022), where he was the driving force behind many innovations.

Zeilinger initiated the founding of the Institute of Science and Technology Austria (ISTA), which is an international research institute for natural and mathematical sciences located in Maria Gugging.

In 2009 Zeilinger founded the International Academy Traunkirchen, which is dedicated to supporting gifted students in science and technology. The educational platform of this Academy includes lectures that are open to the general public, as well as workshops for students and courses for school pupils with talents in the natural sciences. In the summer months the Summer Academy in Traunkirchen runs courses for artists. I also had the great pleasure of organizing several workshops with Anton for the students of our University, where they had to work on various individual topics in quantum physics. At each workshop a renowned physicist was invited to speak, for instance, in 2012 the Nobel Laureate Serge Haroche explained his "*Schrödinger cat*" cavity experiments.

Aside from the Nobel Prize, Zeilinger has received numerous international prizes and awards. Mentioning all of them would be impossible here, but some prestigious examples are: the Micius Quantum Prize (2019), the John Stewart Bell Prize (2017), the Wolf Prize (2010), and the Isaac Newton Medal (2008).

Conclusion

The Bell inequality experiments of the last few decades have had an enormous impact on our view of reality. In my opinion, our perception of reality must be changed radically.

Objects have no properties before observation, in contrast to "*naïve*" realism, and the chronological sequence of observations is irrelevant.

Furthermore, nature is *nonlocal* as implication of Bell's Theorem. But I think, precisely this *nonlocality* feature – which deeply disturbed John Bell since for him it was equivalent to a "*breaking of Lorentz invariance*", what he hardly could accept – could be the key for a deeper and more comprehensive understanding of quantum physics.

All these experiments, which were performed for "philosophical" reasons, also triggered very practical applications, namely quantum information science, which is a prospering field today.

The Call

On Tuesday, October 4th, Anton Zeilinger was sitting at home, working on a paper that he and his group were due to publish. At 11 o'clock the secretary from his Institute called to tell him that there was a person on the phone who insisted on speaking to him but did not want to say why. The call came from a Swedish telephone number. When Zeilinger agreed to take the call, he found the Nobel Prize Committee on the line, who first assured him that "*It's not a fake call*" and then told him that he had been awarded the Nobel Prize in Physics along with Alain Aspect and John Clauser. Anton was speechless, overwhelmed by this wonderful recognition of his work. It came as a shock, but very much a positive one.

Epilogue

On a summer afternoon in 1987, John Bell and I were sitting outside in the garden of the CERN cafeteria, drinking our late 4 o'clock tea. In this relaxed atmosphere I spontaneously said to him: "*John, you deserve the Nobel Prize for your theorem.*" John, for a moment puzzled, replied with seriousness: "*No, I don't. ... it's like a null experiment, and you don't get the Nobel Prize for a null experiment. ... For me, there are Nobel rules as well, it's hard to make the case that my inequality benefits mankind.*"

But, as it turned out, in 2022 the Nobel Prize Committee did indeed conclude that the violation of Bell inequalities was of benefit to mankind and awarded the Prize to Aspect, Clauser, and Zeilinger.

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"Aspect's Experiments" on Quantum Mechanics and Entanglement: a brief historical perspective

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1. Introduction

Theoretical and experimental studies of the properties of light have been intimately associated with the birth and progress of Quantum Physics. It is well known that the whole story of "quantum light" began with Planck in 1900 and Einstein in 1905, and that a major impulse was given by the birth of the laser in the 1960's. In this context, two theoretical works carried out in the 1960's had a major impact on further developments in quantum physics: one by Roy Glauber (Nobel Prize 2005), which laid down the foundations of "quantum optics", and one by John Bell, which paved the way for the experimental tests of the non-separability of quantum mechanics. Bell's work contributed to solve a major debate on the very Foundations of Quantum Mechanics, opened by the famous article of Einstein, Podolsky and Rosen published in 1935. Alain Aspect has made major contributions to both subjects, and is also one of the founders of the research field known as "atom optics", that is an extension of quantum optics from light waves to matter waves. In this article we will not present all of his work, but focus on experiments conducted at Institut d'Optique, in Orsay and then in Palaiseau, from the early 1980's to the late 2010's.

2. A short biography of Alain Aspect

Alain Aspect was born in 1947 in Agen, France. He studied at the Ecole Normale Supérieure de Cachan and Université d'Orsay, and got a degree in physics in 1969. After a master thesis in Optics in 1971, on Fourier Transform Spectroscopy by Holography, he taught during three years in Yaoundé (Cameroun), as an overseas service volunteer.

In 1974 he began a series of experiments on the foundations of quantum mechanics at Institut d'Optique (Orsay), known as "*Experimental Tests of Bell's Inequalities with pairs of Entangled Photons*". This was the subject of his PhD defense (Thèse d'Etat) presented in 1983[1], and the main topic for which he was awarded the Nobel Prize in 2022; more details will be given below. Later, together with his student Philippe Grangier he developed the first *source of single photons*, of a type now called "heralded single photons". This allowed them to carry out a *single photon interference experiment*, which became a classic for textbooks to illustrate the wave particle duality, see also below.

From 1985 to 1992, he worked with Claude Cohen-Tannoudji at the Ecole Normale Supérieure (Paris) and Collège de France, on developing new schemes for cooling atoms with lasers. His main contribution was a method of *Laser cooling below the one photon recoil* by Velocity Selective Coherent Population Trapping (VSCTP). This new method allowed the ENS group to break the so-called "single photon recoil limit", and to demonstrate how this cooling scheme can be embedded in the general framework of Lévy statistics, predicting that there is no theoretical lower limit to the achievable temperature. This type of approach may be important for the development of optical clocks with trapped atoms or ions.

In 1992, he founded a new group of Atom Optics of the Institut d'Optique, which has moved in 2007 from Orsay to Palaiseau, on Campus Polytechnique. More details on the scientific achievements of the group will be given below by David Clément, one of his close collaborators on some of these experiments.

3. Orsay's experiments: testing Bell's inequalities and demonstrating single photon interferences

After the major work by John Bell in 1964 [1], an important conceptual development was the construction of a "testable" inequality by Clauser, Horne, Shimony and Holt in 1969 [2], and the proposal by Aspect in 1976 [3] to enforce Einstein's relativistic separation between measurements, as also initially suggested by Bell [4]. Then there was a succession of increasingly sophisticated experiments, starting with the one carried out by Clauser and Freedman in 1972 [5], up to the three publications by Aspect, Dalibard, Grangier and Roger in 1981-1982 [6a,b,c]. All three experiments performed at Institut d'Optique used a very efficient source of entangled photon pairs, and the third one incorporated for the first time "time-varying" polarization analysers, all designed by Alain Aspect, and built by himself and his team.

The entangled photon source at Orsay was made from a Calcium atomic beam, resonantly excited to the upper level of a two-photon cascade by a Krypton ion laser and a tunable dye laser. Each excited atom decays by emission of

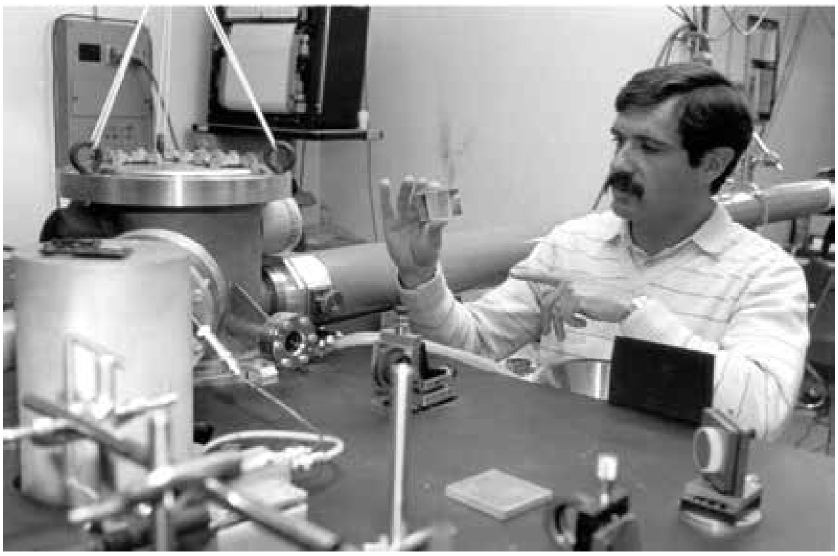

Fig. 1: Alain Aspect showing one of the multidielectric polarization beamsplitters used the experiments [6b] and [6c]. One sees also the atomic beam vacuum chamber where the Calcium atoms were excited up to the upper level of the two-photon cascade. Photo by Lars Becker-Larsen.

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[1] Available at http://tel.archives-ouvertes.fr/tel-00011844

two photons at different frequencies, separated by a time interval corresponding to the exponential 4.7 ns decay time of the intermediate state. Due to the well-chosen angular momentum of the atomic levels, the pair of photons was emitted in the suitable entangled polarization state, as initially proposed and implemented by John Clauser in 1972. However, due to the laser excitation, the pair emission rate in the Orsay experiments was orders of magnitude larger than in Clauser's set-up. The first experiment [6a] used pile-of-plates polarizers like Clauser, but the second one [6b] used multidielectric polarizers (Fig. 1), that were combined with fast optical switches in the last experiment [6c].

The second experiment [6b] had a very high statistical accuracy and violated Bell's inequalities by more than 40 standard deviations, within a few minutes. Due to the more complicated optics the third "switching" experiment had lower count rates, but still achieved a convincing violation by 6 standard deviations. It is worth emphasizing that these violations did not result from iterative improvements, but were obtained at once, as soon as the actual experiment was performed, after a very careful - and very long - adjustment and control of all the parameters. Alain's students certainly remember this specific demand, not so easy to fulfill, but up to the stake of this fundamental test of quantum mechanics (Fig. 2).

Fig. 2: Jean Dalibard, Alain Aspect and Philippe Grangier at the Nobel Lectures for Physics in Stockholm, December 2022. Photo by Laurent Cognet.

In 1985 Alain Aspect moved to ENS, and Philippe Grangier inherited the entire Orsay setup, with the plan to carry out various experiments on single photon interference, this was the subject of his "Thèse d'Etat" under Alain's remote supervision. One idea was to use the Calcium atomic cascade to develop the first source of single photons, of a type nowadays called "heralded single photons". This work introduced a criterion for characterizing single photon sources that is universally used today. In order to fully illustrate wave-particle duality, the idea was to send these individual photons into a carefully designed and very stable interferometer, and to realize a true "*single photon interference experiment*", which became a classic for textbooks [14]. A few years later, another single photon source based on single nitrogen-vacancy center in diamond has been used in *quantum cryptography* [15a]. Also, in a collaboration with the group of Jean-François Roch, Aspect and Grangier participated to an experimental realization of the Wheeler's delayed choice experiment [15b], in a scheme that is an evolution of the 1986 experiment.

On the Bell's inequalities side, many more experiments have been performed since the 1980's, confirming Aspect's results and leaving less and less room for "loopholes" (Zeilinger 1998 [7], Gisin 1998 [8], Wineland 2001 [9]). In addition, new non-locality tests were introduced, e.g. by Greenberger, Horne and Zeilinger [10], providing new perspectives and always confirming and reinforcing the initial work by John Bell. This series of work culminated in three "loophole-free" experiments published in 2015; a nice overview of the story is given by Alain Aspect in "Physics" [11]; see also the other article in this issue.

Parallel to these experiments, the new science of Quantum Information began to develop: scheme for quantum cryptography proposed by Bennett and Brassard in 1984, and relation to entanglement by Ekert [12]; first ideas on quantum computing (Feynman 1982); and finally "explosive" development after the introduction of the factorization algorithm using a quantum computer, proposed by Shor in 1994. A broad overview (in French) is presented in [13].

4. Atoms optics: interferences of matter waves and atom correlations

In 1992, Alain Aspect founded the group of "Atom Optics" of the Institut d'Optique, which in 2007 moved from Orsay to Palaiseau, on Campus Polytechnique. The name chosen by Aspect for this new group indicated the scientific direction he would follow for two decades: the study of the coherence properties of matter-waves and of optics analogs with atoms.

Shortly after Aspect's return to the Institut d'Optique, a milestone was announced in 1995, the observation of Bose-Einstein condensation in a gas of atoms at JILA [16] and at MIT [17]. Bose-Einstein Condensates (BECs), realised with magnetically trapped atoms in three-dimensions (3D), appear when a macroscopic number of bosons occupy the lowest energy state of the trap. This situation can be seen as a matter-wave analog of photons stored in an optical cavity, the central building block of a (photonic) laser. By adding to the trapped atoms the equivalent of a partially reflecting mirror – that which let photons leak out of the cavity, Aspect, in collaboration with Philippe Bouyer, used the atomic BEC as a source to realise an atom laser [18]. The group then characterized the quality of the atom beam, in particular the presence of caustics transverse to the beam propagation, and they introduced a M2 factor defined in analogy to photon lasers [19].

At the same period, the phase of the atomic BEC matter-wave has become the object of intense study. Photon lasers are bright sources of light with a stable phase, well described by the coherent state introduced by Glauber. On the basis of the analogy with photon lasers, the problem of the phase of atomic BECs was raised rapidly [20] and the observation of highly-contrasted interferences between two BECs was reported [21]. These observations provided experimental confirmation of the coherence of 3D isotropic BECs. In contrast, Aspect and collaborators concentrated on elongated, quasi-1D configurations where the phase properties are more subtle. In these elongated BECs, density fluctuations are suppressed but the phase can still fluctuate. Aspect's group produced strongly anisotropic traps using special electromagnets [22] where they were able to observe and characterise the phase fluctuations of quasi-1D BECs [23]. A program specifically devoted to the physics of 1D Bose gases was then initiated, with Christoph Westbrook and Isabelle Bouchoule, exploiting the technology of atom chips [24].

Alain Aspect's ability to identify important scientific questions and to launch himself enthusiastically into the study of new phenomena is exemplified by his works on the Anderson localisation. At the end of 2004, one of us (David Clément) started a PhD thesis with the aim to further probe coherence properties of elongated BECs. However, this plan changed a few weeks later, after Alain had discussed a new problem with Gora Shlyapnikov. The suggestion was to study the localisation of matter-waves in disordered potentials that results from multiple interferences, in analogy to the phenomenon introduced by Phil Anderson for electrons in a solid [25]. It was clear that the coherence properties of 3D atomic BECs allow interference phenomena to be studied. The interest of using atoms lay in the implementation of a well-controlled disorder and in the direct observation of the localised density profile of the matter-wave.

The group decided to shine the atoms with an optical speckle to produce a controlled disorder. Several properties of speckle fields were ideal for a controlled study of localisation phenomena [26] and Pierre Chavel, a colleague from Institut d'Optique, shared with the group his deep understanding of speckle. In the following years, the speckle disorder became a hallmark of Aspect's group in the cold-atom community. The first measurements of BECs expanding in a speckle disorder were obtained in 2005 [27]. Similar experiments were reported in Florence in Massimo Inguscio's group, initiating what Alain would have called a "*friendly competition*". These early experiments of the Orsay and Florence groups were not performed in a regime in which Anderson localisation could occur. Combined theoretical [28] and experimental developments finally led to the observation of Anderson localised matter-waves in 1D [29] (similar results in a bichromatic disorder were obtained in Florence [30]). This milestone was reached thanks to the synergetic effort of many people – including Laurent Sanchez-Palencia , Philippe Bouyer and Vincent Josse - whom Alain had enthusiastically brought together.

The Aspect group has made several landmark contributions to the field of atom optics, i.e. analogs of quantum optics experiments with atoms. In this context, a prerequisite for measuring correlations between atoms, similarly to Quantum Optics with photons, is the detection of individual atoms. At Collège de France, Aspect had already detected metastable helium atoms one by one, exploiting their large internal energy [31]. At Institut d'Optique, he built with Christoph Wesbrook and Denis Boiron a metastable Helium experiment to explore Atom Optics. A major initial achievement was the first metastable Helium BEC in 2001, which was a very risky experimental research because theoretical predictions had many uncertainties - but which finally succeeded in a spectacular way [32]. The group then pioneered an original approach to detect single metastable helium atoms in three dimensions with micro-channel plates. To describe this exceptional detector, usually used in accelerators and high-energy physics, Alain speaks of "*thousands of avalanche photodiodes in parallel*". Nowadays, this detection technique has become the workhorse of cold atom platforms using metastable Helium.

What makes metastable Helium atoms so special is that atoms are annihilated from the metastable state upon detection (decaying to their ground-state), just as photons are annihilated in the photodetection process. Therefore, atom correlations measured with the bosonic species Helium-4 are identical to those obtained in Quantum Optics with photons. Taking advantage of this analogy, the group observed the Hanbury-Brown and Twiss (HBT) effect with atoms [33]. But "*atoms offer more than photons*" and atom optics experiments can also be envisioned with fermions. This new possibility motivated Aspect and his collaborators to move their special detector to Amsterdam, where the group of Wim Vassen had brought the fermionic species Helium-3 to quantum degeneracy. This collaboration led to the detection of both boson bunching and fermion anti-bunching on the same apparatus, combining HBT measurements with Helium-4 and Helium-3 [34]. More recently, the group at Institut Optique focused on another landmark experiment in quantum optics, the Hong-Ou-Mandel (HOM) experiment [35]. The HOM effect is much more complex than HBT-type of effects as it reveals two-particles interferences. By exploiting the creation of momentum-correlated pairs of atoms, the group successfully realised an atomic HOM experiment [36].

The group founded by Alain Aspect has expanded over the years, to bring together six quantum gas setups led by seven permanent researchers and run by many PhDs and postdocs. A photograph taken at the announcement of the 2022 Nobel Prize in Physics gathers this vibrant group of people (Fig. 3).

Fig. 3: Photograph of the Atom Optics group founded by Alain Aspect taken soon after the announcement of the 2022 Nobel prize in Physics. Photo by Jean-François Dars.

5. Conclusion

To conclude, we emphasize that, in addition to his widely acclaimed talent as an experimentalist, the role of Alain Aspect as a charismatic speaker was essential in getting the importance of entanglement (or “quantum non locality”) widely recognized [1]. “Aspect’s experiment” has been an underlying motivation for many physicists to start working theoretically or experimentally on entanglement, especially in the 1980's. Today, Quantum Information is a self-sustained research field, but this underlying motivation is still present, and the role of quantum entanglement is more important than ever.

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The Sakurai Prize 2023 to Heinrich Leutwyler

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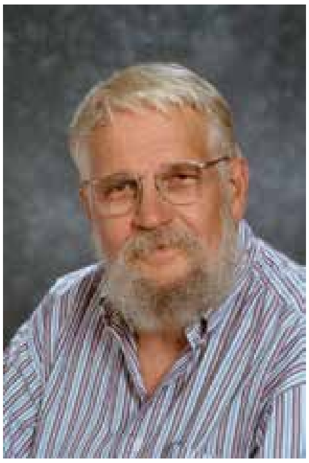

The J. J. Sakurai Prize for Theoretical Particle Physics is awarded yearly by the American Physical Society (APS) "to recognize and encourage outstanding achievement in particle theory". The prize was established in 1984 in memory of the Japanese-American physicist Jun John Sakurai. Heinrich Leutwyler is the first Swiss recipient (for a complete list, see www.aps.org/programs/honors/prizes/sakurai.cfm).

He is honored *"for fundamental contributions to the effective field theory of pions at low energies, and for proposing that the gluon is a color octet".*

Leutwyler acquired the 'Lizentiat' in Physics with Mathematics and Astronomy as minor subjects from the University of Bern in 1960. His PhD thesis "Generally covariant Dirac equation and associated boson fields" was supervised by John R. Klauder, who at that time spent a sabbatical in Bern. After completing this work in 1962, Leutwyler received a fellowship from the Swiss National Science Foundation and the Janggen-Pöhn-Stiftung St. Gallen, which allowed him to broaden his horizon by spending a year as a postdoc in the group of John A. Wheeler at Princeton University. During that stay, he got acquainted with the basic notions of particle physics, which at that time was full of fascinating open questions and puzzles. After his return to the University of Bern, he gradually built up a group working in this field, just in time for it to participate in the revolution that took place in particle physics 50 years ago, when the Standard Model (the quantum field theory of all fundamental interactions except gravity) took shape [1]. The Institute for Theoretical Physics flourished under his leadership and fundamental contributions were made by its members over years to come: many of them authored by Leutwyler himself and in particular with his former doctorand Jürg Gasser. Leutwyler received the 'Venia legendi' in 1965, was promoted to Associate Professor in 1966 and to Full Professor in 1969. He also served as member of the Swiss Research Council and as Dean of the Faculty of Natural Sciences. In the year 2000, he retired from his position at the University, but continues to do research in theoretical particle physics as Emeritus up to this day.

In this article I will try to summarize the part of his work mentioned in the laudatio: the proposal that the gluon is an octet, and the formulation of the low-energy effective field theory of pions — in reverted order with respect to the laudatio to follow the chronological one.

In 1973 Leutwyler made a three-month stay at Caltech and worked together with Murray Gell-Mann and Harald Fritzsch on a paper titled "Advantages of the color octet gluon picture" [1]. Color was the name given by Gell-Mann to a new quantum number which had been postulated for quarks [2, 3] to solve problems with the Pauli principle for their bound states. According to this idea quarks exist in three colors, but bound states are built in such a way as to be color neutral. Whether color played any role in the interaction that keeps quarks bound together in hadrons was an open question. In this article they provided different arguments in favor of a theory in which the force carrier, the gluon, is a color octet (i.e. exists in eight different colors) and against the alternative in which the gluon is a color singlet, i.e. carries no color and is blind to it. The color-octet picture amounts to a nonabelian gauge theory of the SU(3) (color) group and is called quantum chromodynamics (QCD). One of the key arguments in favor of this picture was the discovery, made just a few months earlier by Gross and Wilczek [4] and Politzer [5] (Nobel prize in 2004), that such a theory is asymptotically free. In theories with this property the strength of the interaction diminishes as the energy increases, a behavior which had already been observed experimentally: when probed by collisions of very high energy the quarks inside a proton behaved as if they were free [6]. This contrasts with the fact that it is impossible to extract quarks from a proton (or any other hadron), a property known under the name of confinement. The discovery of asymptotic freedom made very concrete the hope that one theory, and a beautifully simple one, could describe both behaviors. QCD is by now established as the theory of strong interactions beyond any reasonable doubt: for an overview of the development of QCD over the last fifty years, including the early history, see [7].

The first point in the laudatio is about "the effective field theory of pions at low energies", which also concerns the strong interactions, but aims to describe them only in a restricted energy region. The formulation of such a theory was also a collective effort over decades. The basic principles were established already in the sixties and early seventies, mostly under the name of "current algebra", well before the formulation of QCD. At the end of the seventies Steven Weinberg summarized and reformulated this approach in a modern language [8], suggesting how this could be viewed as a quantum field theory too, but of the "effective" kind — a quantum field theory which from the very start aims to be valid and useful only in a certain energy region. This by now famous article by Weinberg was written when this approach had mostly lost its appeal, in large part due to birth of QCD, a candidate for a *fundamental* theory of the strong interactions. So why was Weinberg promoting an *effective*, low-energy theory of strong interactions, six years after the fundamental one had been formulated? And what was the role of Gasser and Leutwyler in the development of the former?

In 1984, following two short letters which stated some of the main results [9], Gasser and Leutwyler published a paper with the title "Chiral Perturbation Theory to One Loop" [10]. This was followed in 1985 by a second one titled: "Chiral Perturbation Theory: Expansion in the Mass of the Strange Quark" [11]. The first one carries out the full program sketched by Weinberg five years earlier and extends it from the S-matrix to Green's functions, in case one considers

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[1] See also Leutwyler's article in: *SPG Mitteilungen* Nr. 50, p. 29 ff, (*https://www.sps.ch/fileadmin/articles-pdf/2016/Mitteilungen_Milestones_10.pdf*)

only the up and down quark masses as small. The second does the same in case also the mass of the strange quark is treated as small. As of today the first one has collected more than 4'500 citations, whereas the second one only slightly less (about 4'200). Such a high number of citations reflects one simple fact: these two papers opened a new field, in fact a very broad and successful one, which is still thriving today and has branched into many ramifications. It is not just a new specific theory, but a new paradigm for how to formulate an effective field theory for systems which undergo spontaneous symmetry breaking.

The key point is the following: when a system undergoes spontaneous symmetry breaking, massless excitations are generated. This has been shown by Goldstone in his famous theorem: the massless states are called Nambu-Goldstone bosons (NGB). For QCD the relevant symmetry is that of chiral transformations: if quarks have no mass, the state in which the spin points in the same direction as the momentum cannot be transformed into a state in which the spin points in the opposite direction. These so-called left- and right-handed components of the quark fields become independent particles, and the strong interactions cannot distinguish between them, nor between the different kinds (flavors) of quarks. One can freely mix the different flavors of the left- and the right-handed components of quarks without any physical effects: what we call up or down or strange for the left- or right-handed quarks is in the massless limit a mere convention. Mathematically, this is called a $SU(N_f)_L \times SU(N_f)_R$ symmetry, with N_f the number of massless quarks. It turns out, however, that the ground state of QCD is not symmetric under these transformations, but only under simultaneous ones for the left- and the right-handed components — which are called vector transformations ($SU(N_f)_V$). According to the Goldstone theorem, massless scalars appear in the spectrum of the theory, which have the same quantum numbers as the generators of the transformations which modify the ground state. For QCD these are negative parity scalars (also called pseudoscalars), and it is indeed the case that the lightest strongly-interacting particles, the pions, have these properties. That they are not exactly massless is explained by the fact that the masses of the up and down quarks are not exactly zero either, but small. This picture was first proposed by Nambu as early as in 1960 [12].

The Goldstone theorem does not only predict the existence of massless excitations: it also has universal consequences like, for example, that the interaction among them vanishes at vanishing momentum. This follows from the peculiar nature of the NGB fields and their transformation properties under the global symmetry of the system [13, 14]. How exactly this works and can be used to calculate observables at low energy has been first shown for the strong interactions, in the leading-order approximation, during the sixties and early seventies. Going beyond leading order was far from trivial but a clear path forward was indicated by Weinberg in his 1979 paper. The work by Gasser and Leuwyler extended these ideas and provided a complete formulation of the theory at next-to-leading order — or, in the language of perturbative quantum field theory, at the one-loop level. In developing the theory it is only the details of the symmetry which are specific to a particular physical system: the principles are however general and can be applied to other systems even beyond particle physics.

Chiral perturbation theory (χPT) is the effective field theory (i.e. a faithful representation) of QCD at low energy. Gasser and Leutwyler showed that to make the connection between the fundamental and the effective theory direct and logically straightforward it was essential to introduce external fields: the symmetry properties of QCD could be simply expressed as invariance properties of the path integral under transformations of the external fields. If the NGB are the only massless states, they are the only dynamical fields one needs to include in the effective Lagrangian. In order to construct the latter all one needs to know are the transformation properties of the NGB fields — those of the external fields are prescribed. Calculating the path integral over the NGB fields provides the desired low-energy representation of QCD: a path integral with the right transformation properties and the correct singularities generated by the exchange of the lightest degrees of freedom. Unfortunately, there are infinitely many invariant terms which have to be included in the effective Lagrangian. However, one can order them according to the number of derivatives (and external fields) which appear in them, so that only a finite number of them has to be kept depending on the level of accuracy one aims at. At leading order (two derivatives or one external scalar field — which is how quark masses are included) only two terms are needed. At next-to-leading order, the effective Lagrangian contains 7 (10) terms for $N_f = 2$ ($N_f = 3$), and these were classified by Gasser and Leuwtyler for the first time [10, 11]. In addition, one needs to evaluate the path integral with the leading order Lagrangian. This is divergent, but the divergences have the form of a local, chiral invariant action of next-to-leading order, and can therefore be reabsorbed by the next-to-leading order Lagrangian — the somewhat counter-intuitive process of renormalizing a nonrenormalizable theory. The level of rigor, clarity and logical linearity of this formulation is to this day stunning and makes these papers true classics.

Deriving explicit expressions for observables from the path integral is straightforward, as Gasser and Leutwyler showed. What one obtains are expressions for them as a simultaneous expansion in momenta (p) and quark masses, taken to be small compared to the typical scale of strong interactions — roughly speaking the mass of the ρ-meson or of the proton ~ 1 GeV. At leading order one obtains expressions up to $O(p^2)$ and at next-to-leading order $O(p^4)$, and many observables were worked out by Gasser and Leutwyler at this order: for example, in [10], the $\pi\pi$ scattering amplitude, and its values at threshold (the scattering lengths, which had been first calculated by Weinberg at $O(p^2)$ in 1966 [15]).

In [11], which included also kaons and the eta in the Lagrangian, the number of calculable observables was significantly extended. In fact this was followed by two further papers dedicated to form factors describing kaon decays [16] and to the $\eta \to 3\pi$ decay [17], which at the time represented a puzzle that χPT at one loop was able to solve. An application of particular interest concerns the quark masses: since in χPT the dependence of observables on quark masses is explicit, it is possible to determine ratios of quark masses by taking ratios of specific observables, most notably meson masses [11, 18, 19]. Thanks to this approach it was concluded very early on that $m_u / m_d \sim 0.5$, whereas the strange quark is much heavier: $m_s / (m_u + m_d) \sim 13$. This approach has been refined and extended over decades and still provides essential information on these fundamental parameters of the Standard Model [20].

In the years that followed, until about the beginning of the nineties, Gasser and Leutwyler worked out further extensions of the formalism, again opening up new research lines. Most notably, they showed that at low temperature the behavior of a gas of hadrons can be precisely described by χPT, which provides a rigorous framework to work out predictions in a systematic expansion in the temperature [21, 22], as well as a rough estimate of the temperature at which chiral symmetry is restored.

In those years the lattice approach to QCD was also making fast progress, thanks to conceptual, algorithmic as well as hardware improvements, but was still far away from making realistic numerical simulations of strong interactions as they occur in nature. The main difficulties were related to the simulation of virtual quark pair creation (neglected in the so-called "quenched approximation"), of sufficiently small quark masses and sufficiently large volumes. While the first was an uncontrolled approximation which had to be overcome at some point (as indeed happened), the latter two difficulties could be addressed by an extrapolation, to be done numerically. Having the guidance of analytic formulae is particularly useful in such cases. For what concerns the quark mass dependence, χPT automatically provided the needed formulae for any observable. It is worth emphasizing at this point that the expansion in quark masses is not just a polynomial expansion, but contains also logarithms of the quark masses, with exactly calculable coefficients [2]. The fact that the infinite-volume extrapolation could also be guided by analytic formulae obtained within the framework of χPT is much less obvious and was pointed out again by Gasser and Leutwyler, who worked out the extension of the theory to the finite-volume case in [24].

Another important and highly nontrivial extension of the approach was that to the sector of the theory with baryon number equal to one, which was worked out by Gasser, Sainio and Švarc [25]. Based on this, the important issue of the determination and theoretical understanding of the pion-nucleon Sigma term was addressed by Gasser and Leutwyler and collaborators [26, 27]. The formulation of the theory in this sector is conceptually particularly complex, because of the presence of one particle in the system (the nucleon), whose mass stays finite in the chiral limit. After the pioneering and fundamental work of Gasser et al. [25], there have been further attempts at improving the formulation, notably the heavy-baryon approach of Jenkins and Manohar [28, 29] and the Lorentz-invariant one by Becher and Leutwyler [30], which are alternative and complementary approaches still used to this day.

Formulating the theory at the one-loop level opened up the question of the understanding of the one-loop and higher-order corrections, as well as of the convergence of the expansion. Both issues were addressed already in the two founding papers [10, 11], but continued to be scrutinized later in more detail. First of all there is the issue of the size of the finite parts of the counterterms (the so-called low-energy constants, or LECs) and whether these could be understood in physical terms. That these were related to the contribution of the lowest lying resonances was discussed in [10] and later studied more systematically in two papers written in collaboration with Ecker, Pich and de Rafael [31, 32]. These clarified the role of the different kinds of resonances and provided an understanding of the size of the LECs, in particular of the larger ones [3].

In addition to the LEC there is also the contributions of pion loops or unitarity corrections. Depending on the observable these may be less or more important and, in some cases, so large as to cast doubts on the possible convergence of the expansion. This issue was addressed already in [10] and in more detail in the paper on $\eta \to 3\pi$ [17], where these corrections are large. How to deal with such cases was discussed in another fundamental paper by Gasser and Leutwyler, written in collaboration with John Donoghue [33], which proposed the combined use of the chiral expansion with dispersion relations. The study concerned the possibility for the Higgs boson to be particularly light, which, at the beginning of the nineties, was not yet excluded experimentally. A Higgs boson with mass of about 1 GeV would have decayed mainly into two pions. The relevant hadronic matrix element for this process is the scalar form factor of the pion, a quantity which had been calculated by Gasser and Leutwyler to one loop [10]. But this would not have been reliable for a Higgs mass significantly above the two-pion threshold. As pointed out in this paper, a dispersion relation allows one to reliably calculate this quantity even up to a mass of about 1 GeV. In this approach χPT still plays an important role as it provides a stringent constraint in the low-energy region. In technical terms: χPT provides values of the subtraction constants of the dispersion relation and the latter a controlled extrapolation to higher energies. With the growing demand for higher precision and extensions to higher energies in the calculation of many different observables and processes, the combined use of χPT and dispersion relations has played a very important and ever growing role over the last thirty years.

A paradigmatic example for the level of precision which can be achieved by this combined approach is provided by the $\pi\pi$ scattering lengths, which have been determined in this way by Gasser and Leutywler, together with myself [34]. At that time the experimental determination of these quantities was still rather uncertain, with quoted values like $a_0^0 = 0.26 \pm 0.05$ and $a_0^2 = -0.028 \pm 0.012$, giving ample room for the one-loop prediction ($a_0^0 \simeq 0.20$ as quoted in [10]) to be proven wrong. Jan Stern and collaborators [35] had pointed out that an experimental value of around 0.26 for a_0^0 would have indicated a surprisingly small value of the quark-antiquark condensate, which is an order parameter of chiral symmetry breaking. This would have meant an unexpected pattern of spontaneous chiral symmetry breaking — closer to that of an antiferromagnet than a ferromagnet. To reach that conclusion, however, it was necessary to show that higher orders in the chiral expansion would not have changed the value of 0.20 significantly. After having calculated the $\pi\pi$ scattering amplitude in χPT at two loops [36] and solved the Roy equations [37] (i.e. the dispersion relations for $\pi\pi$ scattering), all elements were available to obtain a prediction for the scattering lengths on the basis of a matching between the chiral and the dispersive representation. The result of $a_0^0 = 0.220 \pm 0.005$ and $a_0^2 = -0.0444 \pm 0.0010$ shows re-

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[2] The presence of such logarithms had been pointed out early on by Li and Pagels [23], but the fact that the calculation of their coefficients could be made automatic within an effective field theory framework had to wait for the work of Weinberg [8] and then Gasser and Leutwyler [10, 11].

[3] Another way to understand some hierarchies among LEC is the large-N_C expansion [11].

markably small uncertainties and has later been confirmed by experiment [38, 39], thereby excluding the "antiferromagnet-like" scenario of chiral symmetry breaking.

The $\pi\pi$ scattering amplitude was not the first two loop calculation in χPT: the first have been performed by Gasser and collaborators [40, 41] in the early nineties, even before a complete formulation of the theory at this order was available. The need for this had become quite clear, however, and an effort to achieve this was started in the mid-nineties. First with the derivation of the Lagrangian [42, 43], and later with the full renormalization of the theory [44]. With the new millennium χPT entered the era of two loop calculations and quite a few have been made ever since.

In the early nineties Leutwyler also addressed the question of possible loopholes in the derivation of the low-energy effective Lagrangian from the symmetry properties of QCD itself. The issue here is that symmetry arguments in a quantum field theory need to be tested against the possible emergence of anomalies, and Leutwyler [45] was able to prove that the presence of the Lorentz symmetry plays an essential role in excluding these (a similar conclusion was later reached also by d'Hoker and Weinberg [46]). In nonrelativistic systems things are more complicated and the presence of anomalies cannot be excluded: this is what distinguishes the effective Lagrangian of an antiferromagnet from that of a ferromagnet [47].

Space constraints do not allow me to discuss other developments related to χPT and effective field theories of NGB in general. I will conclude by mentioning a few here, just to give an idea of how broad these ramifications are: an even better idea can be gained by browsing through the programs of the series of "Chiral Dynamics" conferences which was started in 1994 at MIT and held every three years at different locations around the world, including Bern in 2009 (for the 30th and 25th anniversary of [8] and [10], respectively). The theory for nonleptonic kaon decays, which was also developed in part in Switzerland [48, 49]; the low-energy effective theory for QCD+QED first developed by Res Urech [50] as a PhD thesis supervised by Jürg Gasser, which was later extended to the presence of leptons [51]. A similar formalism has also been applied to electroweak symmetry breaking, an effective field theory with a completely different energy scale, with early developments starting in Bern [52]. Many variants of χPT have also been developed to cure systematic effects of different lattice formulations and approximations of QCD: quenched and partially quenched χPT [53–57], staggered χPT [58], or to guide the continuum extrapolation [59, 60], to cite only a few. To emphasize the universality character of the approach, let me conclude by citing applications to magnetic systems, which have also been pioneered in Bern [61–63].

I hope that the achievements briefly described here show how well deserved this prize is. For the Swiss physics community this represents reason for pride as well as to cherish and reflect about the favorable conditions of the Swiss university and research system that allowed all this to happen.

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Progress in Physics (94)

Observing the highest energy phenomena in the universe with multi-messengers

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Multi-messenger high-energy astrophysics is the extension of the multi-wavelength exploration of the cosmos with multiple messengers with a common origin, including neutrinos, gravitational waves, and cosmic rays. This branch of astrophysics has currently achieved the potential to unravel the origin of cosmic rays, their relation to the diffuse radiation in the extragalactic space, and their role to forge their galaxies of origin while wandering in their magnetic fields for millions of years. Recent results of IceCube indicate that neutrino astronomy can complement photon astronomy providing insights into opaque sources of high-energy radiation. Starburst galaxies and jetted black holes in active galaxies are favored candidates to explain the diffuse cosmic neutrino background at > 100 TeV energies and its relation to the extragalactic background light. Additionally, gamma-ray bursts remain an intriguing mystery now enriched by joint observations of gamma-rays and gravitational waves. Events with energies up to more than 10 TeV complement these observations possibly opening new windows on new physics.

The galactic diffuse flux, produced by cosmic ray interactions on the interstellar matter of our galaxy and peaking at lower energies, is within the reach of neutrino detectors. Together with the measured galactic gamma-ray flux up to PeV energies, they will shed light on the knee region of cosmic rays and on the possible existence of dark matter in the Galactic plane.

1. Extragalactic diffuse background radiation and cosmic particle fluxes

In 1953, indirect detection of gamma rays from the ground was at its primitive attempts with a photomultiplier (PMT) and a mirror in a garbage can by Galbraith and Jelley [1, 2]. In 1960, Greisen suspected that "*within the next decade cosmic ray neutrino detection will become one of the tools of both physics and neutrino astronomy*" [3]. He also envisaged neutrino astronomy connection with measured cosmic rays (CRs) and with the emerging field of gamma-ray astronomy. In the same year, Markov discussed in a proceeding a vision of deep natural media used as neutrino detectors [4]. After 2 decades, the optical observation of the cataclysmic core-collapse supernova 1987A followed a few hours after the detection of a few neutrino events by the underground detectors Kamiokande, IMB and Baksan. For this, the 2002 Nobel prize was awarded to M. Koshiba [5]. While this set a milestone for multi-messenger astrophysics, the future observation of a similar event would allow a revolution for understanding the formation of compact objects after a supernova collapse by using neutrinos, gravitational waves (GWs) and photons from many bands of the electromagnetic spectrum [6].

The first TeV source from ground, the Crab Nebula, was detected in 1988 by the Whipple telescope in Arizona [7]. In 1990, Ressel and Turner presented the *Grand Unified Photon Spectrum* (GUPS). On the extragalactic background radiation or light (EBL) spanning about 19 orders of magnitude in energy from the radio to the gamma-ray band [8], they superimposed the CR flux, persisting to energies beyond 10^{20} eV, hinting to the existence of extreme extragalactic accelerators. The CR flux extended well beyond the reach of the highest energy colliders on earth, also beyond the reach of *Imaging Atmospheric Cherenkov Telescopes* (IACTs), which at hundreds of TeV recorded only photon flux upper limits. As a matter of fact, high-energy photons are absorbed during propagation by pair production on the diffuse radiation limiting the gamma-ray horizon. Based on the observed energy density of 3 × 10^{-19} eV/cm^3, calculated integrating the measured CR flux above 10^{17} eV [1], it was speculated that *gamma-ray bursts* (GRBs) and black holes and their jets embedded in *active galaxies* (AGNs) are powerful enough to sustain *ultra-high energy cosmic rays* (UHECRs).

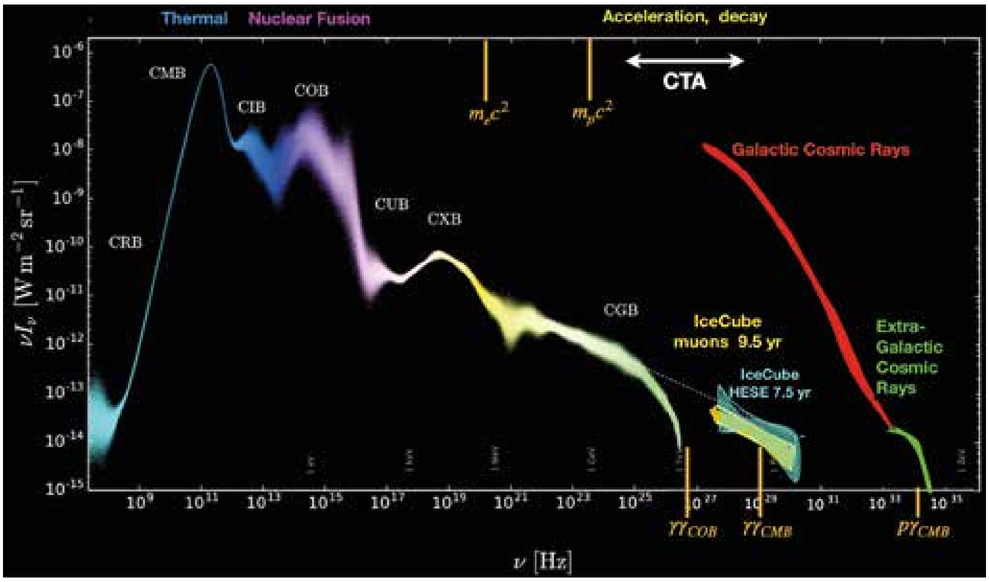

Figure 1: Energy spectrum of EBL from radio to gamma rays in [9] adapted from [10]. The CR spectrum is indicatively drawn from 10^{13} eV [87]. The diffuse spectra of the IceCube HESE sample in 7.5 yr [23] and from the diffuse muon tracks accumulated in 9.5 yr [24] are shown.

Since the first GUPS was presented, the EBL spectrum has been further updated (see the colored spectral emission in Fig. 1 from [9, 10]) using measurements of many experiments. The EBL is dominated by the thermal relic radiation from the last scattering surface observed today as the *Cosmic Microwave Background* (CMB) of ~ 400 photons / cm^3. At about 10 % of it, the *Cosmic Optical Background* (COB) and the *Cosmic Infrared Background* (CIB) play a very relevant role to understand star formation as diagnostic for stellar nucleosynthesis, mass accretion onto black hole processes and gravitational collapse of stars. Optical emission from stars is reprocessed by dust and attenuated by it to be re-radiated in the infrared band. The COB and CIB bumps in the EBL are studied by gamma-ray telescopes in space

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[1] The CR flux is related to the energy density of their sources. For instance, the comparable number obtained for Galactic cosmic rays, integrating their spectrum below the knee energy, is $\rho_E = 4\pi \int_{1GeV}^{10^6 GeV} \frac{E}{\beta c} \frac{dN_{CR}}{dE} dE$ = 1 eV/cm^3, a number comparable to the galactic magnetic field energy density.

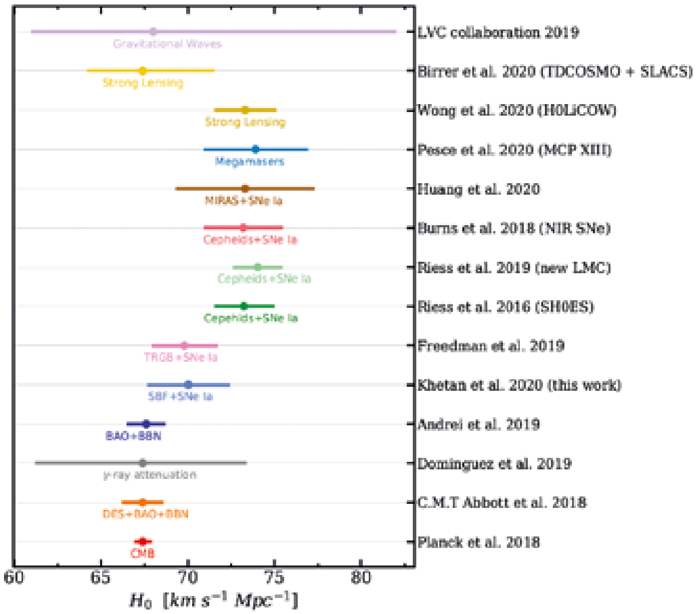

Figure 2: Compilation of Hubble constant late and early universe measurements with inputs from multi-messengers (gamma-rays and GWs). From [17].

and on the ground as they can sample a large population of flaring AGNs at different redshifts *z*. They infer their injection spectra from the measured ones at energies where EBL attenuation is negligible. The effect of attenuation, namely the optical depth as a function of energy and redshift, has been measured by Biteau and Williams using 106 blazar spectra [11], by the Fermi-LAT collaboration with 739 blazars up to redshift $z \sim 3$ and a gamma-ray burst at 4.3 [12]. A joint analysis of 12 blazars using Fermi-LAT and MAGIC data for AGNs with $z \sim 0.03 – 0.944$ covered the widest wavelength region [13]. These measurements offer a new approach to infer the Hubble constant of the late universe and to constrain the matter content in the universe, though these estimates depend on the still large uncertainty on the number density of the EBL as a function of energy. As an example from [14], fitting data combining two different models [15, 16] considering them equally probable, results in the most probable value of $H_0 = 67.4 \pm 6.2$ km·s^{-1}·Mpc^{-1} and $\Omega_m = 0.14 \pm 0.07$ [2], as shown in Fig. 2. Fixing the matter density to $\Omega_m = 0.32$, the obtained value is $H_0 = 65.8 \pm 3.1$ km·s^{-1}·Mpc^{-1} (all errors are at 1σ). This dependency on the EBL uncertainty is a limitation as well as the fact that gamma-ray experiments do not provide the source distance which is taken from optical data. Together with gamma-rays, another new messenger, GWs, contributed such a measurement (see Fig. 2 from [17]). Standard sirens, such as the famous GW170817 neutron star merger, provide the absolute luminous distance D_L from the fit of the gravitational chirp data, hence a simple relation provides H_0 from the known redshift from electromagnetic counterparts: $H_0 \cdot D_L = c \cdot z$ [18]. The uncertainty on H_0 principally depends on the degeneracy between distance and inclination of the plane of the binary system. Both gamma-ray telescopes and GW interferometers have still a limited horizon, despite both GWs and neutrinos are messenger potentially covering a horizon reaching the early universe and propagating through absorbing media in cosmic sources.

Nonetheless, future advanced detectors may make them players to solve the controversy on the early and late universe measurements of the Hubble constant [19]. The *Cherenkov Telescope Array Observatory* (CTAO), thanks to three different sizes of telescopes, will improve this measurement reaching redshifts up to $z \sim 2$ thanks to the better sensitivity by about a factor of 10 and its wide energy range from about 20 GeV to 300 TeV [20]. LIGO and Virgo are expected to reach a few percent precision in 5 yr of data and the Einstein Telescope will reach redshifts beyond 10 becoming a relevant player in cosmology [19].

2. The diffuse gamma-ray and neutrino fluxes

At higher energies than the region of the COB and CIB in Fig. 1, the gamma-ray part of the EBL is named *Extragalactic Gamma-ray Background* (EGB) and it has been measured by Fermi-LAT [21]. When the Galactic Plane contribution is subtracted, only the extragalactic diffuse emission from faint and unresolved extragalactic sources remains, mostly blazars and starburst galaxies. The EGB gives the non-thermal perspective on the cosmos, together with the extragalactic CR flux and the diffuse cosmic flux of neutrinos recently discovered by the IceCube cubic-kilometer neutrino telescope, shown in Fig. 1 [22, 23, 24]. These events are cascade-like when induced by electron or tau neutrinos, or neutral current interactions of all flavor neutrinos with their vertex inside a detector fiducial volume. They are called *high-energy starting events* (HESE) and selected at an en-

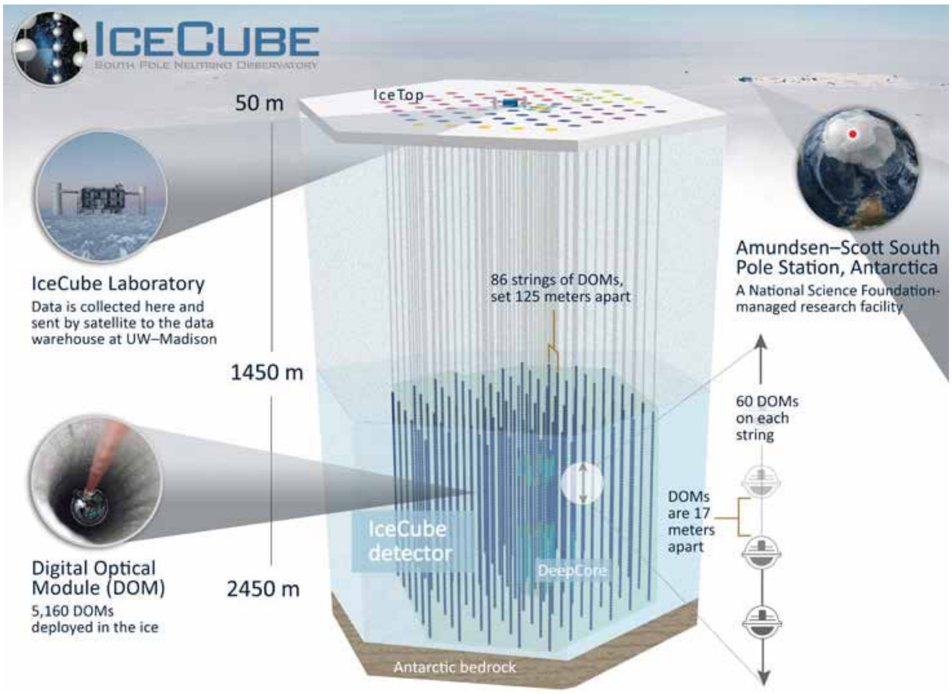

Figure 3: Artistic view of the in-ice detector and the surface extensive air shower array of the IceCube Observatory. In the inserts on the top left the ICLab at the South Pole, also shown in the map on the top right. In the middle on the left a drilled string hole with a Digital Optical Module (DOM) entering in it, on the middle right the inner components of a PMT and a part of a string. There are 86 strings each holding 60 DOMs.

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[2] Each model provides the most likely values of: $H_0 = 71.8 \pm 3.6$ km·s^{-1}·Mpc^{-1} and $\Omega_m = 0.15 \pm 0.06$ for the Finke et al. 2010 model [16] and $H_0 = 63.0 \pm 4.0$ km·s^{-1}·Mpc^{-1} and $\Omega_m = 0.13 \pm 0.06$ for Dominguez et al. 2011 [15].

ergy beyond 60 TeV and over 7.5 yr of data taking [23] is dominated by down-going cascade-like events with limited angular resolution of the order of 10° and energy resolution of about 20 % and a smaller fraction of high-energy neutrino-induced muon tracks with pointing accuracy below 1° and energy resolution of a factor of 2, as muons may be born kilometers outside the detector. Another sample is up-going-muons induced by muon neutrinos selected in an independent analysis using 9.5 yr of data taking [24]. Both the HESE and muon track samples constitute evidence with larger significance than 5σ that cosmic neutrinos are required on top of the background of atmospheric muon and neutrinos to explain the IceCube data.

As seen from Fig. 1, the highest energy end of the multi-messenger plot reveals comparable energy rate densities for the Ultra-High Energy CRs (UHECRs) measured by the *Pierre Auger Observatory* (PAO) [25] and the IceCube neutrinos between 60 TeV to PeV energies. This can be explained by a **unified origin** (as already hypothesized by Ressel and Turner) assuming photo-meson interactions in extragalactic sources [26]. The measurements of these events require challenging detectors. PAO in Argentina includes fluorescence telescopes and sampling detectors of extensive air showers (EAS) covering a surface of 3000 km^2 to detect the time and charge of the electromagnetic and muon components of EAS. IceCube is the first cubic kilometer of ice between 2.5 - 3.5 km depth at the South Pole instrumented with around 5600 optical modules for detecting Cherenkov light of particle showers and muons induced by neutrinos (see Fig. 3). Both are in an upgrade phase towards more sensitive detectors.

The "UHECR-neutrino unification" was discussed in detail by Waxman and Bahcall in 1998, who derived an upper limit on the neutrino flux from extragalactic calorimetric sources, namely sources where CRs lose all their energy in photo-pion production [27]. The chain of pion decay relates neutrinos and gamma-ray secondaries to primary protons or nuclei, namely CRs, as they are the results of proton–proton or proton–photon interactions in cosmic ray sources accelerating protons and ionized nuclei. The Waxman and Bahcall upper bound or **calorimetric limit** [3] is obtained for a fully efficient system for CR energy loss into pion production [4]. This condition corresponds to a diffuse extragalactic neutrino flux upper limit of about $E^2 \frac{dN}{dE} \sim 10^{-8}$ GeV·s^{-1}·sr^{-1}·cm^{-2}. Below this boundary, the system is 'optically thin' and implies that both UHECR and neutrinos originate from systems with an optical depth of less than $\tau_{p\gamma} \sim 0.6$ [28].

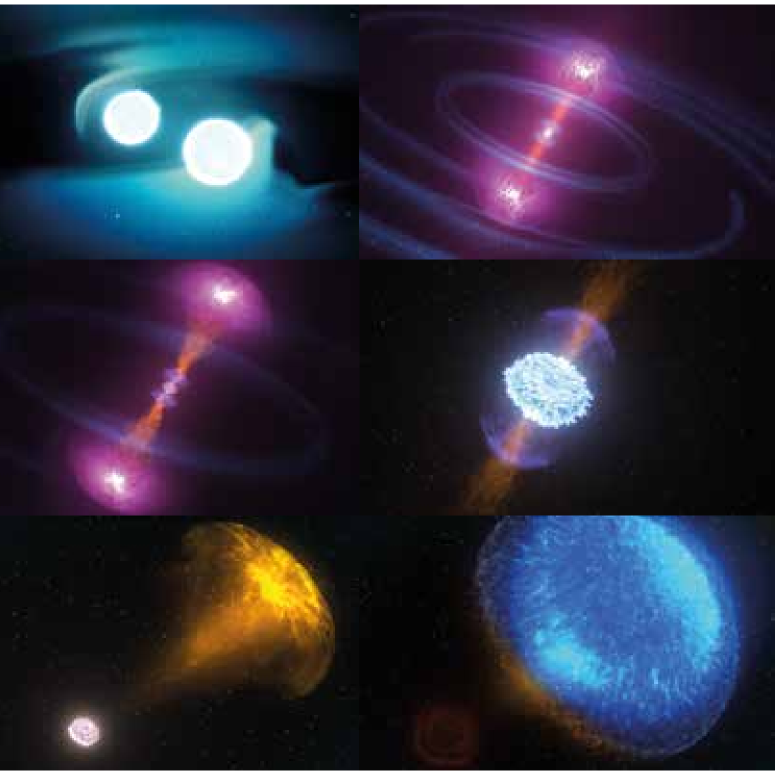

Figure 4: The various phases of a binary star merger producing a GW from the collapsar event and a jet with internal shocks crashing onto the external material to produce a reverse shock (Credit NASA's Goddard Space Flight center/CI Lab, a video can be watched here: https://svs.gsfc.nasa.gov/12740)

Higher neutrino fluxes than this upper bound can be produced in hidden-core AGNs or opaque sources from which only neutrinos escape. The IceCube diffuse flux order of magnitude seems to indicate a large contribution from this topology of sources. Additionally, a joint study between neutrino telescopes (IceCube and ANTARES) and UHECR experiments (PAO and Telescope Array) excluded possible correlations between UHECR directions and neutrinos [29]. This could be due to opaque sources contributing to the diffuse neutrino flux but also to the different horizons of the two cosmic messengers [5].

It has been noted in [28] that, as UHECRs must be accelerated and escape before they lose their energy due to synchrotron radiation, a boundary condition to the magnetic field in the plasma reference frame can be derived. The non-observation of GRBs by IceCube [30, 31, 32] disfavors these powerful yet mysterious sources as accelerators of UHECR sources, as the magnetic field in the jet could overcome this limit in the prompt phase, while the baryon loading might not overcome 10 [33]. Nonetheless, such limit is relaxed by assuming acceleration of heavy nuclei rather than protons and/or models of multiple production zones of neutrinos and gamma-rays.

An extensive review on GRBs with many references is in [34]. In the "canonical" single-zone standard model of GRBs, the prompt phase of gamma-ray emission is due to the ejecta forming an expanding fireball under thermal pressure, with efficient conversion of thermal energy to kinetic energy, then becoming optically thin. These ejecta are caused by the collapse of a rapidly spinning massive star or a binary neutron star merger event forming a powerful engine launching relativistic jets. These dissipate their kinetic energy through accelerating shocks of electrons and protons formed by jet collisions. The prompt phase is followed by an afterglow broadband emission from the radio to gamma-rays, explained by a forward shock formed by the interaction of relativistic jets with the circum-burst material and reverse shock (see Fig. 4).

On Aug. 27, 2017, a splendid example of multi-messenger observation by the three interferometers LIGO and VIRGO of a binary star merger event, GW170817, and the coin-

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[3] The upper bound was criticized as it makes strong assumptions [86], namely that UHECRs are dominantly protons, while in the highest energy end of the spectrum PAO measures heavier composition. The assumed spectrum is E^{-2} fitted from above 10^{19} eV and extrapolated to lower energies, while the energy spectrum might be different.

[4] Namely, the efficiency $f_\pi = 1 - e^{-\tau_{p\gamma}} = 1$ for a very large optical depth of proton-photon interactions ($\tau_{p\gamma} \gg 1$).

[5] In fact, the highest energy neutrinos observed by IceCube could be dominated by sources beyond the O(100) Mpc limited horizon of UHECRs.

cident observation of gamma-rays 1.7 s after it with many observations across the electromagnetic spectrum provided many fundamental physics and astronomical observations (e.g., the Hubble constant determination, the identification of heavy metals in kilonova light curves, the verification of speed of GWs against the speed of light,…) [35]. While this observation directly connected short GRBs to kilonova, this connection is challenged by the long GRB 211211A with optical-infrared emission pointing to a binary merger or kilonova origin [36]. This observation sets the path for the synergy between GW interferometers and the future CTAO, which could be alerted by the merger observations. Observation from ground has proved to be feasible by current ground based IACT arrays and EAS also providing serendipitous observations. GRB 180720B, GRB 190829A and GRB 190114C above 100, 200, 300 GeV have been detected by H.E.S.S. [37] and MAGIC [38] and their measured *Spectral Emission Distributions* (SEDs) favor *Inverse Compton* (IC) scenarios, such as *Synchrotron Self Compton* (SSC) models where emitted synchrotron photons due to gyrating electrons in intense magnetic fields up-scatter by IC on the same emitting lepton population. More recently, GRB 221009A was initially detected by *Swift* and Fermi-GBM and LAT (see Fig. 5) and then detected with significance of about 100σ about 2000 s after the trigger time beyond 500 GeV by LHAASO hybrid array up to about 10 TeV [39]. These observations can be explained by IC scenarios on external seed photons e.g., from the kilonova radiation, named *External Inverse Compton* (EIC), or more exotic phenomena such as axion photon conversion [40].

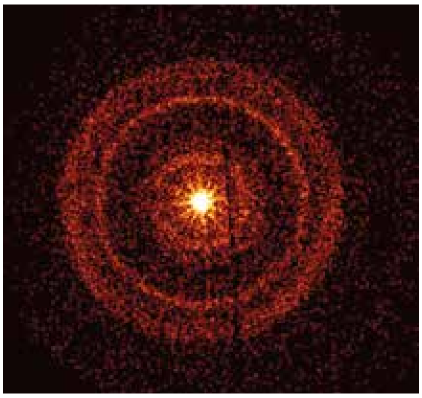

Figure 5: X-ray afterglow captured by Swift of the GRB observed on Oct. 9, 2022 by the detectors on board of the Fermi, Swift and Wind spacecrafts [76].

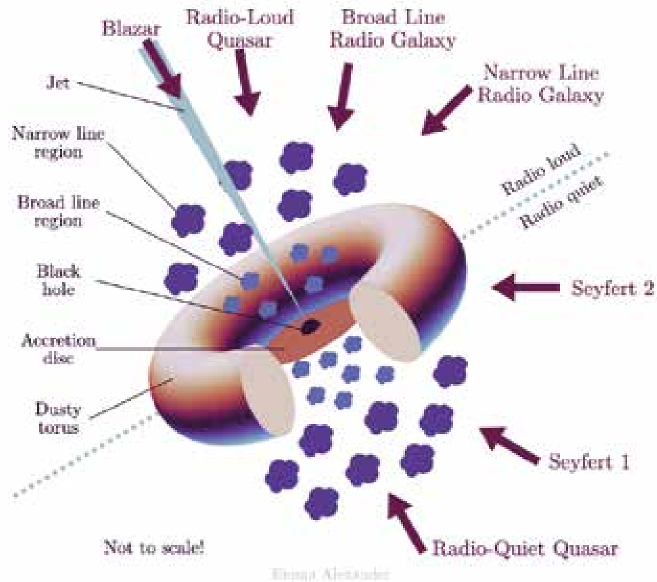

Figure 6 Unification scheme of AGNs (Credit: Emma Alexander, adapted from [82])

In conclusion, while GRBs are disfavored as the UHECR and neutrino sources, we will discuss the case of AGNs (Fig. 6, and see Glossary for more information on what they are).

3. Are active galactic nuclei the sources of the discovered cosmic diffuse neutrino flux?

The evidence of the first neutrino sources took a long time to materialize [41, 26] beginning from DUMAND prototypes [6] in the Pacific Ocean in the 70'ies [42]. A compelling observation of blazars as potential neutrino emitter, relating neutrinos and gamma-rays happened on Sep. 22, 2017. This is expected from CR sources as gamma-rays and neutrinos are the secondaries of hadronic interactions of CRs with matter and ambient radiation. A very high-energy muon neutrino track with most probable energy of 270 TeV was launched as a neutrino alert by IceCube to the astronomical community (IC170922A) [43]. Fermi-LAT and MAGIC follow-up observations [41] confirmed the presence inside the error region of about 0.5° from the IceCube event direction of a flaring blazar, TXS 0506+056, located at redshift of 0.33 with a chance probability of 3σ. Additionally, in an analysis of historical data performed at the University of Geneva, a second neutrino flare was observed in the direction of this source lasting about 100 days between 2014 and 2015 with significance of 3.5σ [44]. While in coincidence with the 2017 neutrino alert a gamma-ray flare was observed, no significant gamma-ray increased-emission was observed during the 2014 - 2015 flare, while two optical flares were detected [45]. These observations cannot be reconciled in models where the high energy emission of gamma-rays and neutrinos is due to single-zone proton synchrotron models.

It was speculated that TXS 0506+056, previously classified as a high-frequency peaked blazar of the class of BL Lacertae (HBL BL Lac) [7], might be a "masquerading" *Flat Spectrum Radio Quasar* (FSRQ) which dissimulate BL Lacs as their broad lines are not clearly visible due to non-thermal jet emission [46]. Typical leptonic models for BL Lacs are SSC models, with synchrotron photons up-scattering by IC on the same emitting lepton population (hence named single zone models), while, for FSRQ, IC can happen on external fields of thermal photons outside of the jet (EIC). Nonetheless, the IceCube observed flares challenge single-zone models as well as EIC and lepto-hadronic models, as the large neutrino flux is in tension with Swift X-ray measurements [47, 48, 49]. More exotic models assuming jet collisions of two jet components, while spine-sheath models [50] have been supported by radio observations [51, 52].

By now several hints indicate that blazars are potentially relevant contributors to the discovered IceCube diffuse neutrino flux. An analysis of IceCube data constrained the blazars in the Fermi 2LAC catalog, as potential contributors to the neutrino diffuse flux up to 27 % (50 %) for unified spectra $E^{-2.2}$ ($E^{-2.5}$) [53], nonetheless under the strong assumption of a common spectral shape for all AGNs. Additionally, in an analysis initiated at the University of Geneva a cumulative emission population study of a 110 catalog of blazars and starburst galaxies produced evidence of an excess at 3.3σ c.l. with respect to the atmospheric background [54].

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[6] Our estimated colleague Peter Grieder, remembered on p. 8 of this issue, was one of the pioneers of the DUMAND project, and a passionate promoter of cosmic ray physics and neutrino astronomy.

[7] HBL and low-frequency peaked LBL are the blazars with the frequency of the synchrotron bump of the SED > 10^{15} Hz or < 10^{14} Hz, respectively.

It is dominated by NGC 1068 and by TXS 0506+056 and PKS 1424+240. TXS 0506+056 and PKS 1424+240 share similar properties compatible to masquerading FSRQ and present hints of neutrino correlation. In addition to what is already discussed about TXS 0506+056, it is noticeable that the location of PKS 1424+240 is compatible with the direction of one of the biggest cascade neutrino events ever observed by IceCube, named Big Bird at PeV energies. After additional hints were collected from a few other blazars, it was speculated that a sub-class of 5 % blazars producing similar fluxes as the observed flux in the TXS 0506+056 long-term flare in 2014 - 2015, could explain the discovered neutrino diffuse flux in 2013 [55, 56, 57]. These could be copious neutrino emitters when inefficient gamma-ray emitters, while the radio and optical emissions generally indicate increasing fluxes. A reanalysis of this catalog with additional 2 years of statistics confirmed this result at 3.7σ c.l. [57].

Noticeably, in the same analyses [54, 57], the Seyfert 2 starburst galaxy NGC 1068 emerged as the hottest source as well as the hottest spot in the full scanned sky map search, despite of the large trial factor. NGC 1068 was one of the first spectroscopic AGN detection with M81 in 1909 [58] and in 1943 Seyfert observed broad line emissions from NGC 1068 and NGC 4151 [59]. Both Seyfert galaxies are compatible with regions with event excesses in IceCube data [57]. For NGC 1068 about 79 signal-like events are fit with a reconstructed spectrum for a single power-law hypothesis of about $E^{-3.2}$ providing evidence at 4.5σ c.l. that neutrinos are messengers from this well-known source at only 14.4 Mpc from us. Nonetheless, this flux is higher by about an order of magnitude than the MAGIC upper limits [60] and the Fermi-LAT flux measured gamma-rays only up to about 10 GeV [61]. The absence of the gamma-ray counterpart to neutrinos in the TeV region triggered AGN corona models [62, 63]. NGC 1068 is a composite system and there might be the contribution of various acceleration processes: it hosts a highly obscured mildly relativistic jet seen in the radio through its accretion disk (as it is a Seyfert 2 galaxy) interacting with interstellar matter or a molecular cloud [64] and eventually originating gamma-rays from IC on IR radiation in the starburst region [65]. Two zone models where gamma-ray emission above 1 GeV results predominantly from the starburst region and TeV neutrinos in the corona have been proposed [66]. Very hard spectra compatible with acceleration of CRs have been obtained in AGN-driven wind models in the circum-nuclear molecular disk [67]. Shock acceleration might take place also in the starburst region, in particular in wind bubbles emerging from the observed radio starburst nuclei with consequent proton-proton interactions [68]. Such a composite object will be an interesting target for CTAO to explore the interplay between the AGN and starburst nature.

4. The granted sources of diffuse neutrinos

Two granted sources of diffuse neutrinos should exist, but marginally contributing to the measured diffuse neutrino flux by IceCube as they are mostly concentrated at lower and higher energies.

Glossary

AGN: Active Galactic Nuclei host large emission lines (differently from stars and galaxies that typically present absorption lines) in their optical spectra and strong luminosity nuclei [59]. They host highly variable cores with a supermassive black hole (SMBH) leading to one of the most efficient processes for energy conversion: the accretion of infalling matter on a SMBH that due to its angular momentum forms a disk of cold material around it. Dissipative processes transport matter inwards and angular momentum outwards, causing heat up of the accretion disc emitting in the optical-ultraviolet waveband, while a corona of hot material forms close to the SMBH horizon emitting up to X-ray energies. Fast outflows or jets with direction along the spin axis of the SMBH can form.

Classifications of AGNs have been for years challenged by the different observed emission characteristics, which are now believed to be caused by the different orientations at which we observe them (see Fig. 6 [82]). Following the classification in [83, 84], radio-quiet AGNs are Seyfert galaxies and characterized by relatively low radio-to-optical flux density ratio (< 10) and radio power at 1.4 GHz < 10^{24} W·Hz^{-1}. For Seyfert 1 galaxies, the observer directly views the nucleus through the Broad Line Region of clouds (BLR), while Seyfert 2 galaxies are viewed through the obscuring structure of the torus surrounding the accretion disk, which obscures the BLR but not the Narrow Line Region (NLR). Radio-loud quasars host jets and are about 10 %, including blazars. They are composed of FSRQ with high excitation lines of emission and BL Lacertae (BL Lacs) with low excitation. Blazars are between AGNs the main gamma-ray emitters, though Seyfert 2 galaxies NGC 1068 and NGC 4945 are also observed in gamma-rays by Fermi-LAT [85]. Blazars have a double-humped spectral emission distribution (SED), with high-energy electrons responsible for the synchrotron radiation in the radio-to-UV bump and gamma-rays due to IC or neutral pion decay from accelerated CRs forming the high energy bump.

CRs: cosmic rays, mostly protons with ionized nuclei in energy-dependent percentages injected by cosmic accelerators and continuously bombarding our atmosphere to produce atmospheric extensive air showers (EAS).

IACTs: Imaging Atmospheric Cherenkov Telescopes. They are ground-based telescopes detecting indirectly gamma-rays through the Cherenkov light produced by secondary EAS in the atmosphere with mirrors and ns-sensitive cameras in their focal plane. The images on the focal plane allow to infer the energy and direction of the primaries and to discriminate the image of a gamma-ray and a cosmic ray shower.

CTAO: The Cherenkov Telescope Array Observatory (see *SPG Mitteilungen* Nr. 68, p. 24) is the new generation of gamma-ray observatory. It will be composed of 2 arrays of IACTs at about 2000 m a.s.l. at the ESO premises in Paranal, Chile, and at the site of Roque de Los Muchachos La Palma, Canary Islands with at least 64 IACTs of 3 sizes covering the 20 GeV - 300 TeV energy range, achieve an angular resolution of about 0.05° above 1 TeV and 2 milli-Crab flux sensitivity in a few years for the Galactic Plane gamma-ray survey.

On the high-energy side, *cosmogenic neutrinos* are expected from interactions of CRs with the CMB in the extragalactic space producing the delta resonance with a threshold of about $10^{19.5}$ eV which fragments in lower energy CRs, gamma-rays and neutrinos. IceCube searches for this neutrino flux and set an upper limit [69]. It should be noticed that, if the UHECR composition is dominated by heavier nuclei than protons, the predicted neutrino flux might be hardly at the reach of current detection [70].

On the low energy side, neutrino telescopes are beginning to observe the granted diffuse neutrino flux produced by *CRs interacting with the interstellar matter* in the Galaxy. Recently, ANTARES published the observation of an excess incompatible with the atmospheric neutrino background at 2σ c.l. with a preferred spectrum of $E^{-2.45}$ from the Galactic Ridge (galactic longitude $|l| < 30°$ and galactic latitude $|b| < 2°$) [71]. Despite the large error, the measured neutrino flux is compatible with a neutral pion decay model from interactions of protons with a power-law spectrum of $E^{-2.4}$, harder than the local CR spectrum of $E^{-2.7}$. The model is normalized to the gamma-ray flux measured by the Fermi-LAT from the same Galactic Ridge region between 19 GeV and 3 TeV [72]. It has been speculated that such a hard spectrum could include the contribution of another component, such as decays of heavy dark matter in the Galactic ridge [73]. Previous results are upper limits to the model in [74] from IceCube only [75] and with ANTARES data, which indicate that the flux will be soon observed [76] and that its contribution to the diffuse IceCube neutrino flux at > 60 TeV is less than 10 % [77]. New analyses exploiting cascade-like events dominated by electron neutrinos will push the energy threshold down increasing sensitivity to the galactic plane flux, as the atmospheric electron neutrino background flux is one order of magnitude lower than the muon one from pion and kaon decays.

New results by LHAASO [78, 79] and Tibet Asγ [80] extend in the ultra-high energy tail the measurement of the flux from the Galactic Plane up to PeV energies, indicating the presence of *PeVatron* accelerators in the Galaxy, still mysterious as standard Diffuse Shock Acceleration (DSA) applied to supernova shocks only achieves one order of magnitude lower energies. IceCube and the KM3NeT upcoming neutrino telescope in the Mediterranean Sea in synergy with CTAO, LHAASO and Tibet Asγ have the potential to unravel the origin of the bending in the CR spectrum at about 4 PeV, called the *knee* [81, 77, 78], to understand its propagation or acceleration origin, explore diffusion processes in the Galaxy and dark matter in the Galactic Plane.

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Progress in Physics (95)

LHCb restores lepton universality

Lesya Shchutska and Renato Quagliani, Institute of Physics, EPFL

Since several years, a consistent pattern of possible deviations from the standard model of particle physics has been building up in studies of the *B* mesons decays involving leptons. One of the most striking measurement was done in flavour changing neutral current channels where the best theoretical precision is achieved, showing a 3.1 standard deviation discrepancy to the standard model and leading to a lot of debate in the scientific community and beyond. However, the latest measurement from the LHCb experiment, carried out with the data collected between 2011–2018 while employing new data analysis techniques, restore the lepton universality in these transitions. The important updates are also done in semileptonic B meson decays at LHCb and high-energy searches with tau leptons at CMS.

1 History behind

Precision measurements of rare processes in particle physics traditionally have been paving the road towards insights about the nature of the fundamental interactions and of the building blocks of matter. Several times in the history of scientific breakthroughs unexpected experimental results led to new theoretical proposals culminating in building the complete theory of the Standard Model of particle physics (SM). As of 10 years now, this theory is complete after the discovery of the Higgs boson by the ATLAS and CMS experiments at CERN, and there is no clear guidance where a new discovery in particle physics might come from.

In this context, a series of deviations from the theory in *B* meson decays has led to a lot of excitement in the particle physics community, as it could signify a beginning of the exploration of so sought for beyond the Standard Model physics, as discussed in detail in Ref. [1]. The picture is formed with several different measurements in the decays corresponding to a $b \to s\ell\ell$ transition, which is forbidden at the lowest-order level and can happen only via processes involving exchange of the heavy virtual particles. Thus the predicted properties of such a process could be easily modified by a presence of new, yet undiscovered, particles. The deviations are seen in the angular distributions and differential branching fractions of the decays corresponding to the $b \to s\mu^+\mu^-$ transition, which can be rather precisely measured experimentally, e.g. at the LHCb, but the theoretical predictions of which still have rather large uncertainties. Finally, the particular interest was gathered by the results of the measurement of the so-called *R* variable, which represents a normalized ratio of branching fractions $\mathcal{B}$ of the *B* meson decays to a final state with two muons and of these to two electrons:

$$R_X = \frac{\mathcal{B}(B \to X_s\mu^+\mu^-)}{\mathcal{B}(B \to X_s e^+e^-)} \Big/ \frac{\mathcal{B}(B \to X_s J/\psi_{\to\mu^+\mu^-})}{\mathcal{B}(B \to X_s J/\psi_{\to e^+e^-})}, \qquad (1)$$

where X_s is one hadron carrying strangeness or a combination of hadrons. To achieve better experimental precision, an additional normalization factor known to be equal to 1, is added to the definition of the R_X variable. In the SM, this ratio is expected to be equal to 1 with high precision, thanks to the equal interaction strength between the force carriers and three families of matter particles, leptons in this case. This property is called *lepton universality*.

The reported patterns of anomalies included lower than expected branching fractions of the decays involving muons in the final state, and R_X for several possibilities of *X* lower than 1. Finally, the latest R_K value was measured to be below 1 by slightly more than 3 standard deviations, adding up with other decay modes going in the same direction.

2 New lepton universality test in $b \to s\ell^+\ell^-$

Recently, a new LHCb result with a simultaneous measurement of the R_K and R_{K^*} in two kinematical regimes each has been released [2, 3], accompanied by a dedicated CERN seminar. All four measurements are found to be close to 1 and compatible with the SM at the level of 0.2 standard deviations as shown in Fig. 1.

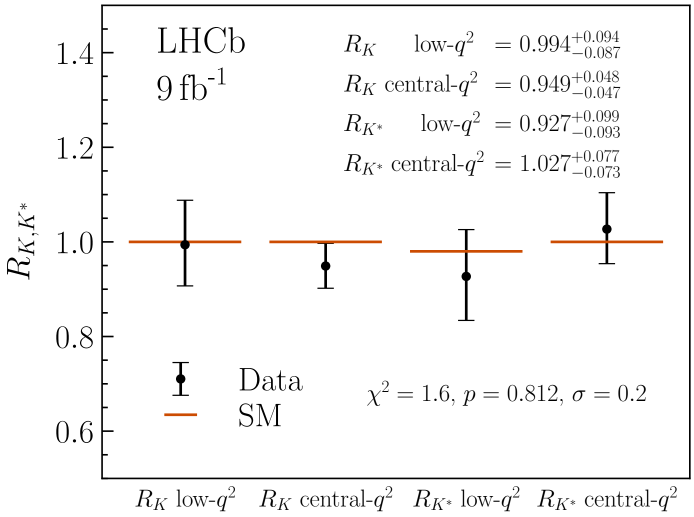

Figure 1: Measured R-values for $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays in two kinematical regimes each, ℓ represents e or μ. Adapted from [3].

The reason for such a qualitative change in the picture is a better understanding of the detector performance with measurement of the electrons. The new analysis employed new multivariate techniques for the electron identification in the detector, which led to realize that the contribution from misidentifying a hadron as an electron in this measurement could be important. In such cases, the abundant *B* decays, as e.g. $B \to K^+K^+K^-$ or $B \to K^+\pi^+\pi^-$ could mimic a rare signal mode of $B \to K^+e^+e^-$, and modify the measured rate of this process. A dedicated method has been developed in order to estimate the contribution of such processes with a result for the $B \to K^+e^+e^-$ decay mode shown in Fig. 2. Due to the peaking structure of this background, it has been contributing to enhance the measured yield in the electron mode, as is shown in Fig. 3. Similar contributions of such a background is found in other analyzed decay modes. After its

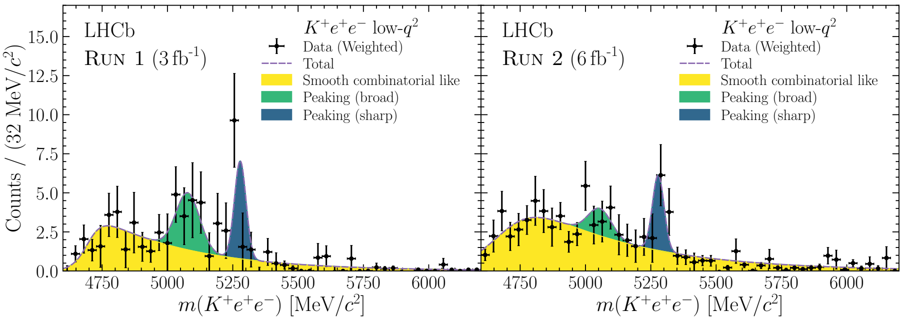

Figure 2: Estimated contribution of the background from processes where at least one hadron is misidentified as an electron in the $B^+ \rightarrow K^+e^+e^-$ decay mode. Adapted from [3].

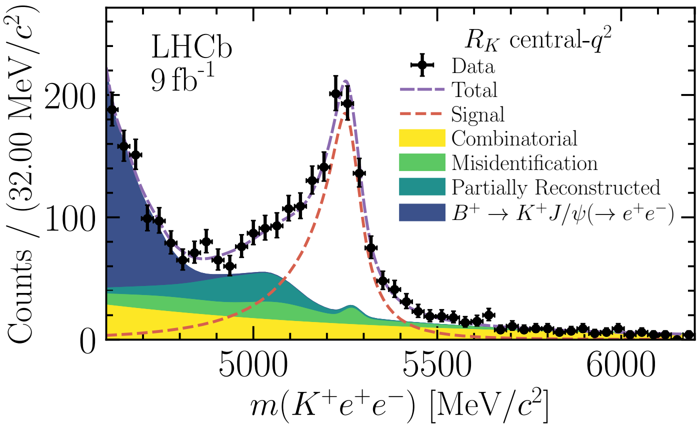

Figure 3: Mass distribution in the $B^+ \rightarrow K^+e^+e^-$ decay mode, with the results of the fit overlaid. Contributions of various backgrounds are shown as extracted from the fit. Adapted from [3].

inclusion to the fit model, the measured lepton universality comes back in line with the SM expectation.

Now, the LHCb detector is set up to collect one order of magnitude more data than previously, which would allow to push the lepton universality measurements to a new level of precision. It is not excluded that the effect is still there but not at the magnitude which was reported previously.

3 New measurements in semileptonic *B* decays

Another transition, challenging lepton universality, is a much more abundant b → c$\ell\nu$ process, for which several experiments provided measurements of the ratios *R*(*D*) and *R*(*D**), defined as

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \text{ where } \ell = \text{e or } \mu.$$

These measurements hint that there might be a difference in fundamental interactions of third generation of leptons, τ, and their lighter counterparts, electrons and muons. Recently, LHCb released a new combined measurement of *R*(*D*) and *R*(*D**) [4], which is shown together with previous results as well as with a new world average in Fig. 4. While the new individual measurements are compatible with the SM at the level of about 2 standard deviations (σ), the world average remains away from the theory prediction by more than 3.2 σ.

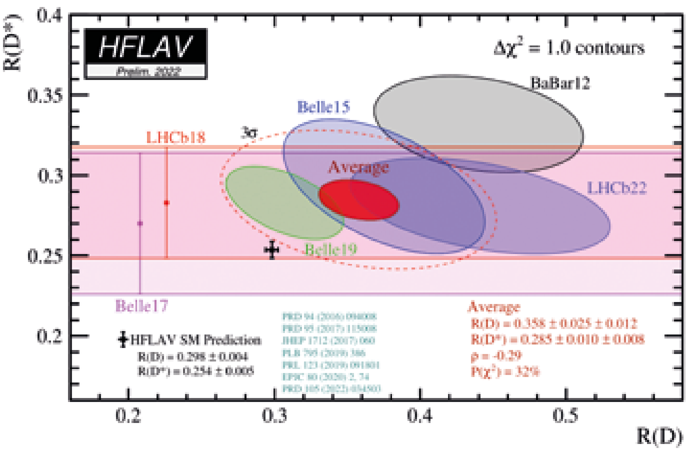

Figure 4: The world status of R(D) and R(D) measurements compiled by the HFLAV collaboration including the latest result from the LHCb collaboration marked as "LHCb22".*

4 High-energy tau leptons

The flavor anomalies have stirred an interest to look for a direct production of particles which could lead to perceived different interaction strength of the three lepton families, with a specific interest to the third generation of fermions. Recently, CMS has released a preliminary result [5] based on the full available dataset, where the search for leptoquarks (LQ) coupling to a τ lepton and a *b* quark in different LQ production scenarios has been presented. In some LQ scenarios, an excess with a significance of 3.4 σ above the SM expectation is observed in the data, as shown in Fig. 5.

ATLAS collaboration has also performed a search for LQ in the final states with tau leptons and *b* jets [6], however the observed results are consistent with the expectations, and no excess is reported.

5 Future prospects

The large experiments at the LHC have restarted their data-taking, and are expecting to significantly increase the amount and quality of the dataset available for the analysis. While one piece of the puzzle has been resolved, and came

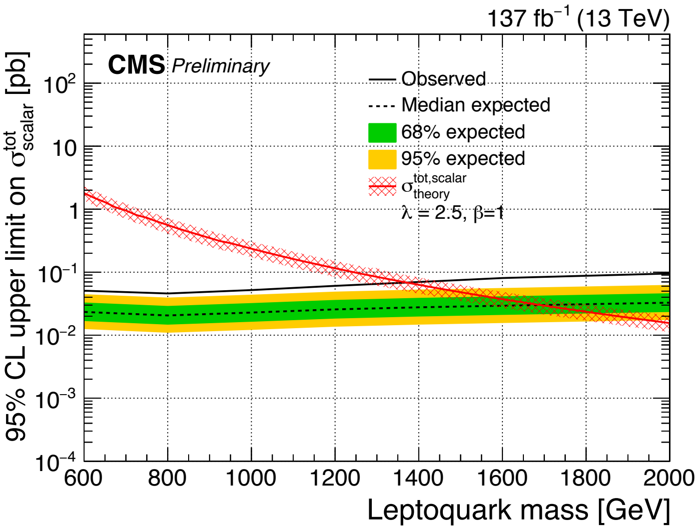

Figure 5: The observed and expected upper limit on the total cross section of a scalar LQ signal with λ = 2.5 at 95 % confidence level. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95 %, respectively, of the distribution of limits expected under the background-only hypothesis. Adapted from [6].

back to the SM prediction, quite a few other measurements, such as differential branching fraction of exclusive $b \to s\ell\ell$ transitions, their angular distributions, as well as $R(D^{(*)})$ observables, require further studies, complemented with the direct searches for the new particles at the ATLAS and CMS experiments. Given the interest of the community to these measurements, we can expect new results with larger dataset in the near future.

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Physik Anekdoten und persönliche Erinnerungen (26)

Kepler, Platon und Schläfli

Bernhard Braunecker

Abb. 1: Johannes Kepler

Johannes Kepler (1571 - 1630) zählt zu den bedeutendsten Wissenschaftlern in der Geschichte der Menschheit (Abb. 1). Die mit seinem Namen verbundenen drei Gesetze werden von vielen als Beginn der modernen Astronomie gesehen. Ihre Formulierung gelang Kepler erst, als er sich von den kosmischen Modellansätzen löste, die er noch in seinem Jugendwerk *Mysterium Cosmographicum* (1597) angewandt hatte. Im Folgenden zeigen wir, dass diese aus heutiger Sicht unhaltbaren Annahmen dennoch erstaunlich gute Abschätzungen über die Radien der Orbitbahnen der damals bekannten sechs Planeten lieferten [1].

Keplersche Triplekonstellation

An der SPG Jahrestagung 2021 in Innsbruck wurde in einer Spezialsitzung anlässlich des 450. Geburtstags von Kepler über seine erfolgreiche, wenn auch nicht reibungslose Zusammenarbeit mit dem Schweizer Jost Bürgi (1552 - 1632) und dem Dänen Tycho Brahe (1546 - 1601) um 1600 in Prag berichtet [2]. Die fachliche Kompetenz dieser Triplekonstellation mit Kepler als genialen Wissenschaftler, Bürgi als herausragenden Pragmatiker und Brahe als gut vernetzten Manager schuf die Voraussetzungen für das später publizierte epochale Werk der keplerschen Gesetze.

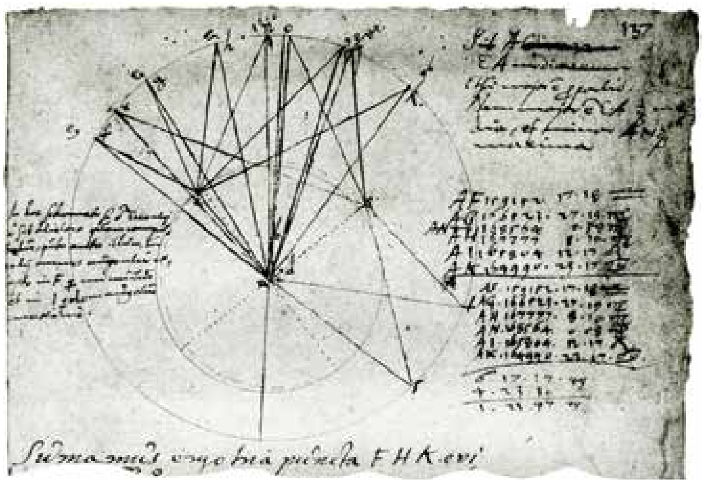

Abb. 2: Das Bild zur Marsbahn aus Band XX, Teilband 2, Seite 132 der Gesammelten Werke Keplers.

Der entscheidende Durchbruch gelang Kepler, wie er später in seinem Werk *Harmonices Mundi* (1619) erklärte, als er die kopernikanischen Annahmen verwarf, demzufolge die damals bekannten sechs Planeten Merkur bis Saturn sich auf Kreisbahnen um die Sonne bewegen würden. Stattdessen führte er zuerst ovale, dann elliptische Bahnen ein und konnte so beim Planeten Mars die Bahnbewegungen in quantitativ guter Übereinstimmung mit den Beobachtungen beschreiben (Abb. 2). Allerdings konnte Kepler nicht die Ursache der Bewegung erklären; das gelang erst im Jahre 1687 Isaac Newton (1643 - 1727), also Generationen später mit dem Gravitationsansatz.

Das platonische Modell

Gibt es nun, wie der Titel dieses Artikels andeutet, eine weitere fruchtbare keplersche Triplekonstellation und diesmal sogar mit Personen, die Hunderte, ja Tausende von Jahren von Kepler trennten?

Dazu soll im Folgenden ein Blick auf Keplers bereits erwähntes Jugendwerk *Mysterium Cosmographicum* von 1597 geworfen werden. Seine damalige Vorstellung vom Kosmos beruhte auf den fünf platonischen Körpern, a) dem Oktaeder aus acht Dreiecken bestehend und die *Luft* symbolisierend, b) dem Ikosaeder (zwanzig Dreiecke, *Wasser*),

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[1] https://www.jostbuergi.com/2021/10/22/warum-hat-jost-b%C3%BCrgi-nicht-die-keplerschen-gesetze-der-planetenbewegung-entdeckt/

[2] https://www.sps.ch/fileadmin/articles-pdf/2021/Mitteilungen_PT012021.pdf

c) dem Dodekaeder (zwölf Fünfecke, *Kosmos*), d) dem Tetraeder (vier Dreiecke, *Feuer*) und e) dem Hexaeder (Würfel mit sechs Quadraten, *Erde*) (Abb. 3), die in dieser Reihenfolge geschachtelt angeordnet sind mit der Sonne im gemeinsamen Zentrum.

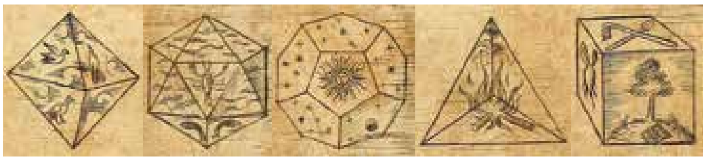


Abb. 3: Die fünf platonischen Körper

Da es in jedem der fünf platonischen Körper sowohl eine Innenkugel gibt, die all seine Flächenelemente von innen berührt, als auch eine umhüllende Aussenkugel, auf der alle seine Eckpunkte liegen, passte Kepler nun die Planetensphären so ein, dass sie einmal die Aussenkugel eines Körpers sind, gleichzeitig aber auch die Innenkugel des nach aussen folgenden nächsten Körpers. So ist die Bahn der Erde einerseits die Aussenkugel des Ikosaeders, anderseits die Innenkugel des Dodekaeders.

Die Anordnung der Körper in Abb. 3 von links nach rechts gibt die Reihenfolge der kosmischen Schachtelung an. So liegt das Oktaeder zwischen Merkur und Venus, das Ikosaeder zwischen Venus und Erde, das Dodekaeder zwischen Erde und Mars, das Tetraeder zwischen Mars und Jupiter und der Würfel zwischen Jupiter und Saturn. Durch diese nahtlose Schichtung waren somit die Radien der Kugelschalen, das heisst die der Kreisbahnen der Planeten, rein geometrisch definiert. Abb. 4 zeigt die räumliche Anordnung der fünf platonischen Körper mit der Sonne im gemeinsamen Zentrum.

In Tabelle 1 sind zeilenweise die sechs Planeten Merkur bis Saturn aufgeführt, sowie jeweils der gemessene Radius ihres Orbits um die Sonne in AE, der astronomischen Einheit. Die Grösse η_1 gibt das Verhältnis der gemessenen Radien benachbarter Planeten an. In den Spalten "Historisches Modell" sind die berechneten Radien der Innenkugel R_I und der Aussenkugel R_A für die fünf platonischen Körper angegeben, allerdings in noch zu bestimmenden Einheiten *a*.

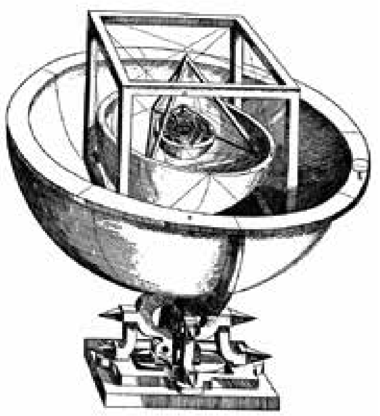


Abb. 4: Aus Keplers Mysterium Cosmographicum

Ihre Berechnung erfolgt mit Hilfe der nach dem Mathematiker Ludwig Schläfli (siehe Box) benannten *Schläfli Indizes*[3] *p* und *q*, welche eine einfache Beschreibung von Polygonen, Polyedern, Parkettierungen usw. erlauben. Für platonische Körper[4] gilt: Man erhält für den Radius der Aussenkugel $R_A = a/2 \cdot \tan(\pi/q) \cdot \tan(\beta/2)$ und für den Radius der Innenkugel $R_I = a/2 \cdot \mathrm{ctg}(\pi/p) \cdot \tan(\beta/2)$. Dabei ist $\beta = 2 \cdot \mathrm{asin}\{\cos(\pi/q) \cdot \sin(\pi/p)\}$. Daraus folgt für das Verhältnis $\eta_2 = R_A \,/\, R_I = \tan(\pi/p) \cdot \tan(\pi/q)$. Vergleicht man die η_2 Werte mit den aus aktuellen Messwerten abgeleiteten η_1 Werten, so ergeben sich Differenzen von maximal 20 %, was erstaunlich gut ist.

Beispiel: So berührt die Jupiterbahn den Hexaeder (Würfel mit Kantenlänge a_{Hexa}) als Innenkugel mit Radius $0.5 \cdot a_{Hexa}$, während der Saturn als Aussenkugel den Radius $\sqrt{3}/2 \cdot a_{Hexa}$ einnimmt. Das Verhältnis $\sqrt{3} : 1 = 1.732$ entspricht bis auf etwa 6 % dem Verhältnis der astronomischen Messwerte 9.60 AE / 5.20 AE = 1.842.

Man kann mit den Werten aus Tabelle 1 die Orbitradien im historischen Modell abschätzen (Tabelle 2), braucht dazu allerdings die Körpereinheiten a_{Okta} bis a_{Hexa}. Hier nutzt man aus, dass die vier Planeten Venus bis Jupiter jeweils in zwei platonischen Körpern vorkommen. Beispiel: Der Orbitradi-

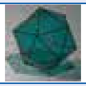
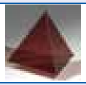
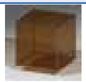
Moderne Astronomie			Historisches Modell							Fehler
Planeten			Platonischer Körper		Schläfli Index		Kugelradien			
	R_{Orbit} (AE)	η_1			p	q	R_I	R_A	$\eta_2 = R_A / R_I$	$(\eta_1 - \eta_2) / \eta_1$
Merkur	0.39									
		1.87	Oktaeder (Luft)		3	4	0.408	0.707	1.73	8 %
Venus	0.72									
		1.38	Ikosaeder (Wasser)		3	5	0.756	0.952	1.26	10 %
Erde	1.00									
		1.52	Dodekaeder (Kosmos)		5	3	1.114	1.401	1.26	21 %
Mars	1.52									
		3.41	Tetraeder (Feuer)		3	3	0.204	0.612	3.00	14 %
Jupiter	5.20									
		1.84	Hexaeder (Erde)		4	3	0.500	0.868	1.73	6 %
Saturn	9.60									

Tabelle 1: Orbitradien der sechs Planeten, sowie die Radienverhältnise benachbarter Planeten η_1 bestimmt aus modernen astronomischen Messungen und η_2 unter Benützung des platonischen Modells.

---

[3] https://de.wikipedia.org/wiki/Schläfli-Symbol

[4] https://de.wikipedia.org/wiki/Platonischer_Körper

us von Merkur ist nach Tabelle 1 $r_{Merkur} = 0.408\ a_{Okta}$. Unter Benutzung der Daten der Venus findet man $a_{Okta} = 0.756 / 0.707\ a_{Ikosa}$. Wegen $r_{Erde} = 0.952\ a_{Ikosa}$ wird somit $r_{Merkur} = (0.408 \cdot 0.756) / (0.707 \cdot 0.952)\ r_{Erde} = 0.46\ r_{Erde}$ im Vergleich zum genauen Wert von $0.39\ r_{Erde}$.

Dabei werden die Abweichungen von den heutigen Messwerten wegen der Fehlerfortpflanzung mit zunehmender Entfernung des Planeten von der Erde grösser.

Planet	Moderne Astronomie (AE)	Historisches Modell (AE)
Merkur	0.39	0.46
Venus	0.72	0.79
Erde	1.00	1.00
Mars	1.52	1.26
Jupiter	5.20	3.77
Saturn	9.60	6.54

Tabelle 2: Orbitradien der sechs Planeten nach dem historischen Modell im Vergleich zu heutigen Messdaten, jeweils in AE.

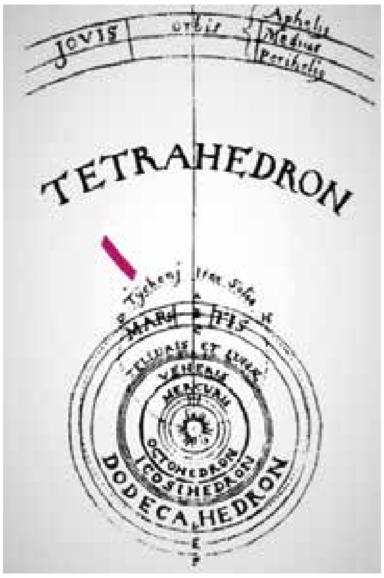


Abb. 5: Schalenanordnung der Planeten und der platonischen Körper

In Abb. 5 aus *Harmonices Mundi* ist das Schachtelungskonzept dargestellt. Interessant ist die eingezeichnete geozentrische Bewegung der Sonne um die Erde gemäss der Vorstellung Tycho Brahes, bei der alle anderen Planeten jedoch weiterhin um die Sonne kreisen (roter Strich).

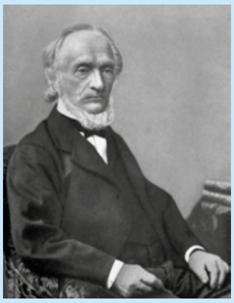
Obwohl die Diskrepanzen trotz der unrealistischen Modellannahme erstaunlich klein sind, wurden sie von Kepler als Wissenschaftler nicht akzeptiert, weshalb er das Modell später verwarf. Nur warum liess er sich in jungen Jahren auf diese mehr philosophisch geprägte Modellierung ein?

Kepler als Esoteriker

Für Kepler und viele Wissenschaftler seiner Zeit hatten Natur und Wirklichkeit noch einen verborgenen Sinngehalt, der sich nur dem Esoteriker, dem Suchenden und Wissenden erschloss. Ihre Welterkenntnis beschränkte sich nicht auf das Rationale, sondern suchte bewusst die Natur in allen ihren Gestaltungen zu erfassen. Nicht nur messbare Quantitäten wie Anzahl, Gewicht, Beschaffenheit und Bewegungen, sondern auch Qualitäten, in denen Sinnliches und Übersinnliches, Körper und Geist, Glaube und Wissen als Gesamtes erfahren werden, mussten vom Suchenden betrachtet werden.

Kepler war in diesem Sinne Naturphilosoph mit stark theologischen Vorstellungen. Er wollte das Himmelsystem verstehen und suchte als Neo-Platoniker stets auch nach dem Sinn von Naturerscheinungen, der sich nicht messen liess. Das war für ihn kein Widerspruch zu seinen astronomischen Studien, da die Hauptaufgabe des Astronomen das Erstellen von Horoskopen für seinen Arbeitgeber oder für wichtige Personen war wie das hier gezeigte für den Feldherrn Albrecht von Wallenstein (Abb. 6). Diese, aus heutiger Sicht pseudowissenschaftliche Tätigkeit, führte jedoch zur Gründung weiterer Universitäten, da astrologische und somit astronomische Fragestellungen nicht von der Kirche behandelt wurden.

Ludwig Schläfli (1814 - 1895) war ein Schweizer Mathematiker, der sich mit Geometrie und Funktionentheorie beschäftigte. Er wurde 1848 zum Privatdozenten ernannt, 1853 zum ausserordentlichen Professor und 1872 schliesslich zum ordentlichen Professor an der Universität Bern. Er spielte eine Schlüsselrolle bei der Entwicklung des Begriffs der *Dimension*, welcher unter anderem eine entscheidende Rolle in der *Physik* spielt. Obwohl seine Ideen heute in jedem Grundstudium in Mathematik behandelt werden, ist Schläfli selbst unter Mathematikern eher unbekannt [1].



Mit ihm verwandt ist **Alexander Friedrich Schläfli** (1832 - 1863), der sein gesamtes Vermögen der Schweizerischen Gesellschaft für Naturwissenschaften (SGN) vermachte unter der Bedingung, "dass die Gesellschaft [...] einen jährlichen und immerwährenden Preis über eine Frage der physikalischen Wissenschaften stiften soll". Seit der ersten A. F. Schläfli-Preis Verleihung im Jahr 1866 haben bis heute mehr als 100 Preisträgerinnen und Preisträger diesen Preis erhalten [2].

---

[1] Erwin Neuenschwander: "Schläfli, Ludwig", in: *Historisches Lexikon der Schweiz (HLS)*, Version vom 09.08.2011. *https://hls-dhs-dss.ch/de/articles/028934/2011-08-09/*

[2] Heinz Balmer: "Schläfli, Alexander", in: *Historisches Lexikon der Schweiz (HLS)*, Version vom 09.08.2011. *https://hls-dhs-dss.ch/de/articles/032096/2011-08-09/*

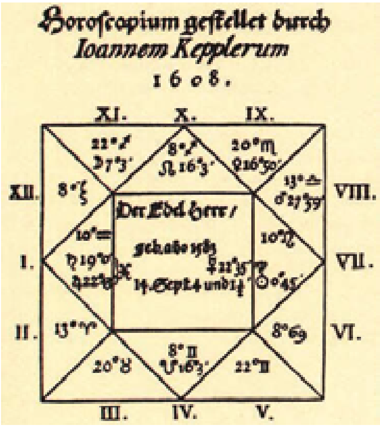


Abb. 6: Horoskop von Wallenstein

Schlusswort

Die Tatsache, dass ein esoterisches Modell, das in der Tradition der antiken pythagoreischen Schule wurzelt, sich über ein Jahrtausend hielt und erstaunlich gut die Beobachtungsdaten wiedergab, ist schon bewundernswert. Hier könnte man in Anlehnung an das Zitat von Wolfgang Pauli: „*Das ist nicht nur nicht richtig; es ist nicht einmal falsch*“ bemerken, dass der platonische Ansatz, die Planetenradien durch geometrische Eigenschaften hochsymmetrischer Körper zu beschreiben, so grossartig und kühn ist, dass er nicht mal wahr sein muss.

History and Philosophy of Physics (31)

Wolfgang Pauli and the discovery of his Exclusion Principle hundred years ago

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1 Introduction

In this article I shall sketch how Pauli arrived at the exclusion principle hundred years ago. At the time – before the advent of the new quantum mechanics – the exclusion principle was not at all on the horizon, because of two basic difficulties: (1) There were no general rules to translate a classical mechanical model into a coherent quantum theory, and (2) the spin degree of freedom was unknown. It is very impressive indeed how Pauli arrived at his principle on the basis of the fragile Bohr-Sommerfeld theory and the known spectroscopic material. The Pauli principle was not immediately accepted, although it explained many facts of atomic physics. In particular, Heisenberg's reaction was initially very critical, as I will document later. My historical discussion will end with Ehrenfest's opening laudation [1] when Pauli received the Lorentz medal in 1931. This concluded with the words: "*You must admit, Pauli, that if you would only partially repeal your prohibitions, you could relieve many of our practical worries, for example the traffic problem on our streets.*" According to Ehrenfest's assistant Casimir who was in the audience, Ehrenfest improvised something like this: "*and you might also considerably reduce the expenditure for a beautiful, new, formal black suit*" (quoted in [2], p. 258).

Let me begin with a few biographical remarks. Pauli was born in 1900, the year of Planck's great discovery. During the high school years Wolfgang developed into an infant prodigy familiar with the mathematics and physics of his day.

2 Pauli's Student Time in Munich

Pauli's scientific career started when he went to Munich in autumn 1918 to study theoretical physics with Arnold Sommerfeld, who had created a "nursery of theoretical physics". Just before he left Vienna on 22 September he had submitted his first published paper, devoted to the energy components of the gravitational field in general relativity. As a 19-year-old student he then wrote two papers about the recent brilliant unification attempt of Hermann Weyl (which can be considered in many ways as the origin of modern gauge theories). In one of them he computed the perihelion motion of Mercury and the light deflection for a field action which was then preferred by Weyl. From these first papers it became obvious that Pauli mastered the new field completely.

Sommerfeld immediately recognized the extraordinary talent of Pauli and asked him to write a chapter on relativity in *Encyklopädie der mathematischen Wissenschaften*. Pauli was in his third term when he began to write this article. Within less than one year he finished this demanding job, beside his other studies at the university. With this article [3] of 237 pages and almost 400 digested references Pauli established himself as a scientist of rare depth and surpassing synthetic and critical abilities. Einstein's reaction was very positive:

> *"One wonders what to admire most, the psychological understanding for the development of ideas, the sureness of mathematical deduction, the profound physical insight, the capacity for lucid, systematic presentation, the knowledge of the literature, the complete treatment of the subject matter or the sureness of critical appraisal."*

Hermann Weyl was also astonished. Already on 10 May 1919, he wrote to Pauli from Zürich:

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

Pauli studied at the University of Munich for six semesters. At the time when his Encyclopedia article appeared, he obtained his doctorate with a dissertation on the hydrogen molecule ion H_2^+ in the old Bohr-Sommerfeld theory. In it the limitations of the old quantum theory showed up.

In the winter semester of 1921/22 Pauli was Max Born's assistant in Göttingen. During this time the two collaborated on the systematic application of astronomical perturbation theory to atomic physics. Already on 29 November 1921, Born wrote to Einstein: "*Little Pauli is very stimulating: I will never have again such a good assistant.*" Well, Pauli's successor was Werner Heisenberg.

3 Discovery of the Exclusion Principle

Pauli's next stages were in Hamburg and Copenhagen. His work during these crucial years culminated with the proposal of his exclusion principle in December 1924. This was Pauli's most important contribution to physics, for which he received a belated Nobel Prize in 1945. Since this was made before the advent of the new quantum mechanics, I ask you to forget for a while what you know about quantum mechanics.

The discovery story begins in fall 1922 in Copenhagen when Pauli began to concentrate his efforts on the problem of the anomalous Zeeman effect. He later recalled: '*A colleague who met me strolling rather aimlessly in the beautiful streets of Copenhagen said to me in a friendly manner, "You look very unhappy"; whereupon I answered fiercely, "How can one look happy when he is thinking about the anomalous Zeeman effect?" '.*

In a Princeton address in 1946 [4], Pauli tells us how he felt about the anomalous Zeeman effect in his early days:

> *“The anomalous type of splitting was on the one hand especially fruitful because it exhibited beautiful and simple laws, but on the other hand it was hardly understandable, since very general assumptions concerning the electron, using classical theory as well as quantum theory, always led to a simple triplet. A closer investigation of this problem left me with the feeling that it was even more unapproachable (...). I could not find a satisfactory solution at that time, but succeeded, however, in generalizing Landé’s analysis for the simpler case (in many respects) of very strong magnetic fields. This early work was of decisive importance for the finding of the exclusion principle.”*

What was known at the time when Pauli began with his work

I would like to show you now in some detail what Pauli did in his first step [5]. In doing this, I use ‘modern’ (post-quantum mechanics) notations and first summarize the state of knowledge at the time when Pauli did his work.

- The energy levels of an atom determine the spectrum by *Bohr’s rule*:

  $$E_2 - E_1 = h\nu .$$

- In spectroscopy some *quantum numbers* were already associated to energy levels, namely [1]:
  - L [$= k - 1$], $L = 0, 1, 2, 3,...$ (S, P, D, F,...), our present day orbital angular momentum.
  - S [$= i - ½$]: Each term belongs to a singlet or multiplet system, characterized by a *maximal* multiplicity $2S + 1$ ($S = 0, ½, 1, ...$), reached with increasing L. S is our present day spin quantum number.
  - The various terms of a multiplet, having the *same* L and S, are distinguished by a quantum number J [Sommerfeld’s j], which takes the values:

    $$J = L + S,\ L + S - 1,...\ L - S \text{ for } L \geq S,$$

    $$J = S + L,\ S + L - 1,...\ S - L \text{ for } L < S.$$

    J is our present day total angular momentum. The maximal multiplicity $2S + 1$ is reached for $L \geq S$.

- One knew the following *selection rules* (valid in most cases):

  $$L \rightarrow L \pm 1,$$

  $$S \rightarrow S,$$

  $$J \rightarrow J + 1,\ J,\ J - 1 \ (0 \rightarrow 0 \text{ forbidden}).$$

- For a given atomic number Z ($Z - p$ if the atom is ionized p times) the following holds:

  Z even → S, J: integer,

  Z odd → S, J: halfinteger.

- *Splitting in a magnetic field*:
  - Each term splits into $2J + 1$ terms, distinguished by a quantum number M taking the values $M = J, J - 1, ..., -J$.
  - *Landé*: If the field is *weak*, the terms are equidistant and their deviation from the unperturbed term is $\Delta E_M = M \cdot g(\mu_0 B)$, where $\mu_0 = e\hbar/2mc$ is the Bohr magneton (introduced by Pauli in 1920) and g is Landé’s g factor:

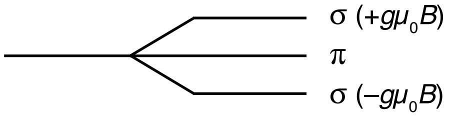
    $$g = \frac{3}{2} + \frac{S(S+1) - L(L+1)}{2J(J+1)} \ ;$$

    (extracted from empirical data; not understandable on classical grounds.)
  - *Selection rules* for Zeeman transitions:

    M → M ± 1 (σ–component),

    M → M (π–component).

    If the g factors for the initial and final states are the same, we have the following Lorentz triplet (*normal* Zeeman effect):



Step 1: Zeeman effect for strong fields and Pauli’s sum rule

Pauli accepts these *empirical rules* as established, and proceeds to investigate the spectroscopic material for *strong* fields (Paschen-Back case). In a table he gives the energy splitting’s ΔE as multiples of $\mu_0 B$ and describes the result as follows:

> If two quantum numbers M_L, M_S [$= m_1, \mu$] are introduced, whose sum is equal to M,
>
> $$M = M_L + M_S,$$
>
> and which take the values
>
> $$M_L = L,\ L-1, ...,\ -L,$$
>
> $$M_S = \begin{cases} \pm\frac{1}{2} & \text{for doublets (alkali atoms)} \\ 0, \pm 1 & \text{for triplets (alkaline earths)} \end{cases} ,$$
>
> then the following simple formula holds for strong fields:
>
> $$\Delta E/\mu_0 B = M_L + 2M_S = M + M_S.$$

Pauli *generalizes* this at once to arbitrary multiplets, assuming that the same formula holds, but that M_S takes the values

$$S,\ S - 1,\ ...,\ -S.$$

This generalization was at the time not experimentally tested.

The selection rule for M_S is: $M_S \rightarrow M_S$, hence the Zeeman effect is *normal for strong fields*. Thus the situation is simpler in this case.

As the main point of the paper Pauli postulates a remarkable formal rule which allows him to derive Landé’s whole set of g factors. Pauli’s sum rule reads:

> *“The sum of the energies of all states of a multiplet belonging to given values of M and L remains a linear function of B, when we pass from weak to strong fields.”*

(In quantum mechanics this rule follows immediately [2])

SPECIAL CASES:

1) $M = J = L + S$. Then there is only *one* state, whose energy must be linear in B.
2) If M is chosen such that there are $2S + 1$ states (the maximal possible number) then the arithmetic mean of

---

[1] In square brackets I give the historical notation.

[2] The sum in Pauli’s rule is the trace of $<H_B>$, $H_B = \mu_0 B(J_3 + S_3)$, where $<H_B>$ is the perturbation matrix for fixed M. This trace is obviously linear in B. For this we have from the anomalous Zeeman-effect and the Paschen-Back-effect two alternative expressions. Their equality leads to the following equation

$$\sum_{M_L, M_S}^{M_L+M_S=M} \frac{M_L + 2M_S}{M_L + M_S} = \sum_J g(J; L, S) \ .$$

> their energies ΔE_M in strong magnetic fields is $M\mu_0 B$. Hence Pauli's sum rule, which later became known as *Pauli's g-permanence rule*, implies that the mean of all factors is equal to 1, for all $L \geq S$.

Pauli now shows – and he puts most weight to this – that all factors *g* can uniquely be calculated from the energies for strong fields. Pauli verified this only numerically, but claimed that "it is possible to carry through the calculation also algebraically instead of numerically". (This is shown in the biography [2] on Pauli by Charles P. Enz, on p. 164.)

Pauli was very unhappy when he wrote this paper, which only later turned out to be important. In several letters he laments about his 'unfortunate work on the anomalous Zeeman effect'. To Sommerfeld he wrote [3]:

> *"I have long vexed myself with the anomalous Zeeman effect and often lost my way. I considered and discarded untold assumptions. But it just wouldn't ever work out! In this I have miserably failed for once up to now! For a time I was quite desperate ... I have written all of this with a tear in the corner of my eyes and am anything but delighted."*

In the final section of his paper he expresses very clearly why he believes that the presently known principles of quantum theory will not lead to an understanding of the anomalous Zeeman effect. Since I find it very difficult to preserve the characteristic style of Pauli's writing I quote only the German original:

> *"Eine befriedigende modellmässige Deutung der dargelegten Gesetzmässigkeiten, insbesondere der in diesem Pararaphen besprochenen formalen Regel ist uns nicht gelungen. Wie schon in der Einleitung erwähnt, dürfte eine solche Deutung auf Grund der bisher bekannten Prinzipien der Quantentheorie kaum möglich sein. Einerseits zeigt das Versagen des Larmorschen Theorems, dass die Beziehung zwischen dem mechanischen und dem magnetischen Moment eines Atoms nicht von so einfacher Art ist wie es die klassische Theorie fordert, indem das Biot-Savartsche Gesetz verlassen oder der mechanische Begriff des Impulsmomentes modifiziert werden muss. Anderseits bedeutet das Auftreten von halbzahligen Werten von m und j bereits eine grundsätzliche Durchbrechung des Rahmens der Quantentheorie der mehrfach periodischen Systeme."*

After his return to Hamburg Pauli began to think about the closing of electronic shells. He was convinced that there must be a closer relation of this problem to the theory of multiplet structure. In his Nobel Prize lecture he writes:

> *"I therefore tried to examine again critically the simplest case, the doublet structure of the alkali spectra. According to the point of view then orthodox, which was also taken over by Bohr in his lectures in Göttingen, a non-vanishing angular momentum of the atomic core was supposed to be the cause of this doublet structure."*

In his next paper [6] Pauli rejected this 'orthodox' point of view, and introduced instead a classically non-describable two-valuedness of the electron, now called the spin.

Step 2: Two-valuedness of the electron

Let me show you in some detail how he arrived at this fundamental conclusion. First, he calculates the relativistic corrections upon the magnetic moment and the orbital angular momentum of electrons in the K-shell. For the ratio of the two he finds with simple classical arguments

$$\frac{|\vec{M}|}{|\vec{L}|} = \frac{e}{2mc}\left\langle\left(1-\frac{v^2}{c^2}\right)^{1/2}\right\rangle_{\text{time}} .$$

According to the virial theorem the time average on the right must be equal to the total energy of the electron in units of mc^2. For the latter Pauli uses Sommerfeld's relativistic formula and finds for the K-shell ($L = 0$, $n = 1$) the value $(1-\alpha^2 Z^2)^{1/2}$ for the relativistic correction factor ($\simeq 1-\frac{1}{2}\alpha^2 Z^2/n^2$ for an arbitrary n).

Adopting the 'orthodox' point of view, Pauli now calculates the relativistic correction on the anomalous Zeeman effect, using his earlier results – in particular his sum rule. I do not have to tell you this in detail, because it turns out that this influence on the g-factors is *not* compatible with experience. The empirical factors *g* are rational numbers depending only on the quantum numbers of the term. The result is summarized by Pauli as follows:

> *"In order to explain the observed factors g by means of an angular momentum of closed shells, such as the K-shell of the alkali atoms, one would have to assume a doubling of the ratio of magnetic to mechanical momentum for electrons in the shell, and also a compensation of the classically computed relativistic effect of velocity,"*

Pauli rejects this logical possibility. Instead he assumes that closed shells have no angular momentum and no magnetic moment. This implies that in the case of alkali atoms the angular momentum of the atom and its change of energy in a magnetic field are ***due to the valence electron only***. In Pauli's words:

> *"Insbesondere werden bei den Alkalien die Impulswerte des Atoms und seine Energieänderungen in einem äusseren Feld im wesentlichen als alleinige Wirkung des Leuchtelektrons angesehen, das auch als Sitz der magneto-mechanischen Anomalie betrachtet wird."*

So far Pauli had only made a critical analysis of an existing hypothesis, but now comes a big jump when he writes:

> *"According to this point of view the doublet structure of alkali spectra as well as the deviation from Larmor's theorem is due to a particular two-valuedness of the quantum theoretical properties of the electron, which cannot be described from the classical point of view."*

Since Pauli does not explain these prophetic words any further in this second paper, it may be helpful if I add a few remarks. For *strong* fields he had the formulae

$$M = M_L + M_S,\ \Delta E/\mu_0 B = M_L + 2M_S.$$

Pauli follows Sommerfeld and interprets *M* in his next paper as the total angular momentum in the direction of the field.

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[3] *"Ich habe mich sehr lange mit dem anomalen Zeemaneffekt geplagt, wobei ich oft auf Irrwege geriet und eine Unzahl von Annahmen prüfte und dann wieder verwarf. Aber es wollte und wollte nicht stimmen! Dies ist mir bis jetzt einmal gründlich danebengegangen! Eine Zeit lang war ich ganz verzweifelt ... ich habe das Ganze mit einer Träne im Augenwinkel geschrieben und habe davon wenig Freude."*

(Sommerfeld also introduced the quantum number J.) For alkali atoms the closed shells do not contribute to M nor to the magnetic moment. Hence,

$$M = m_\ell + m_s,\ \Delta E/\mu_0 B = m_l + 2m_s,$$

where m_ℓ, m_s are the values of M_L and M_S for the single valence electron. The integer number m_ℓ may be interpreted classically as the orbital angular momentum in the direction of the field. Therefore, m_s is an *intrinsic* contribution of the electron to the total angular momentum M in the direction of the field which must be added to m_ℓ. We have already seen that for the alkali doublets m_s takes the values ±½.

Since m_ℓ is an integer it follows that M is a half-integer, and since J of a multiplet is defined to be the maximal value of M, we have for the *two terms of an alkali doublet*

$$J = L \pm ½.$$

Thus, the two-valuedness of J, which is responsible for the doublet splitting, is a direct consequence of the two-valuedness of m_s. This explains the first part of Pauli's key sentence:

> *"...the doublet structure of alkali spectra (...) is due to a particular two-valuedness (...) of the electron."*

What exactly did Pauli mean concerning "the deviation of Larmor's theorem"?

In the paper of Pauli I have just discussed he uses the well-known formula for the energy of an atom in a magnetic field

$$\Delta E = -\vec{M} \cdot \vec{B}\,, \qquad \vec{M}\text{: magn. moment.}$$

If we compare this with his expression for strong fields, we see that an atom behaves in a strong field like a magnet having a magnetic moment $\mu_0(M_L + 2M_S)$ in the direction of the field. For a single valence electron this is equal to $\mu_0(m_\ell + 2m_s)$.

So far strong fields have been assumed. But if we consider an S state of an alkali atom, we have $M_L = 0$, $M = M_S = m_s$, and now the formula $\Delta E/\mu_0 B = 2m_s$ holds – by Pauli's sum rule – for *weak* fields too. This means: For S states the magnetic moment of alkali atoms is equal to $\underline{2m_s\mu_0}$ (the famous $g = 2$). According to Pauli, this magnetic moment is *entirely due to the valence electron*.

Pauli did not attempt to give a meaning to the fourth degree of freedom in terms of a model. In his Nobel Prize lecture [7] he said about this:

> *"The gap was filled by Uhlenbeck and Goudsmit's idea of electron spin, which made it possible to understand the anomalous Zeeman effect. (...) Although at first I strongly doubted the correctness of this idea because of its classical mechanical character, I was finally converted to it by Thomas' calculations on the magnitude of doublet splitting."*

Step 3: The exclusion principle

In his decisive third paper [8] Pauli first summarizes his previous results for alkali metals. For these the quantum numbers L, J, M of the atom coincide with those of the valence electron for which we use the modern notation ℓ, j, m_j. (Pauli's notation is: $k_1 = \ell + 1$, $k_2 = j + ½$, $m_1 = m_j$.) Beside these there is, of course, also the principle quantum number n. As already explained, the number j is equal to ℓ ± ½. Pauli emphasizes:

> *"The number of states in a magnetic field for given ℓ and j is $2j + 1$, the number of these states for both doublets with a given ℓ taken together is $\underline{2(2\ell + 1)}$."*

For the case of *strong* fields, Pauli adds, one can use instead of j the quantum number $m_2 := m_j \pm ½$ $(= m_j + m_s)$, which directly gives the component of the magnetic moment parallel to the field. (We would use for the Paschen-Back region the four quantum numbers n, ℓ, m_ℓ, m_s.)

Next, Pauli extends the "formal classification of the valence electron by the four quantum numbers n, ℓ, j, m_j to *complicated atoms*". This is performed with the help of Bohr's *principle of permanence* (*Aufbauprinzip*), which says: If, to a partially ionized atom, one (or more) electron is added, the quantum numbers of the electrons already bound remain the same as in the ionized atom. Pauli shows that in simple as well as in more complicated cases the application of this principle gives just the right variety of terms for the atom.

For Pauli's further line of thought the formulae for the Zeeman effect in *strong* fields are again essential. First, the principle of permanence implies that one can associate quantum numbers m_j for the individual electrons, the sum of which is the total angular momentum of the atom in the direction of the field:

$$M = \sum m_j\ .$$

By the same rule, the magnetic moment $(M + M_S)\mu_0$ is also equal to the sum of the moments $m_2\mu_0$ of all the electrons, i.e.,

$$M_2 := M_L + 2M_S = M + M_S = \sum m_2\ .$$

In the sums m_j and m_2 have to assume *independently* all values which belong to the quantum numbers j, ℓ. Pauli checked (for instance for neon) that this gives the correct results for the Zeeman terms.

This result, he says, suggests the following hypothesis: "*Every electron in the atom can be characterized by its principle quantum number n and* ***three additional quantum numbers*** *ℓ, j, m_j*". As for the alkali spectra, j is always equal to ℓ ± ½. For strong fields the quantum number $m_2 = m_j \pm ½$ is used instead of j.

It must be emphasized that Pauli had to assume a magnetic field so strong that every electron has, *independently* of the others, a definite mechanical angular momentum m_j and a magnetic moment m_2 (in units of μ_0), but he notes that for thermodynamic reasons (invariance of the statistical weights under adiabatic transformations of the system) the number of states in weak fields must be the same as in strong fields. In an article of van der Waerden [9], I have made heavy use of in this section, this is commented as follows:

> *"It is clear that the definition of these quantum numbers presented great difficulties at a time when quantum mechanics did not exist and the types of motion of the electron had to be described by inadequate classical models. (...) We have to admire Pauli's courage and persistence*

> *in developing the logical consequences of his hypothesis. The subsequent development of quantum mechanics led to a complete justification of every one of his assumptions."*

Next, Pauli considers the case of *equivalent electrons*. First of all he notes that in this case some combinations of quantum numbers do *not occur in nature*. For instance, if two valence electrons are in *s* states belonging to different values of *n*, we observe a singlet *S* term and a triplet *S* term. If, however, both electrons have the same *n*, *only the singlet term occurs*. For Pauli the question arises, which quantum theoretical rules govern this behavior of the terms.

This reduction of terms, Pauli says, is closely connected with the phenomenon of closed shells. About this E. C. Stoner [10] had recently made a new proposal which deviated from Bohr's theory of the periodic system. For example, Bohr had divided the 8 electrons of the *L*-shell into two subgroups of 4 electrons. Stoner, on the other hand, proposed to divide the electrons into a subgroup of 2 electrons having $\ell = 0$, and a subgroup of 6 electrons with $\ell = 1$. Generally, for any closed shell and every value of $\ell < n$, Stoner associated a *subgroup of* $2(2\ell + 1)$ *electrons*.

Even more important was Stoner's remark that the same number $2(2\ell + 1)$ is also equal to the number of states of an *alkali atom in a magnetic field* belonging to the same value of ℓ and to a given principle quantum number of the valence electron. This remark of Stoner gave Pauli the clue to his exclusion principle. He explains the fact that there are exactly $2(2\ell + 1)$ electrons in every subgroup of a closed shell by assuming that every state, characterized by the quantum numbers (n, ℓ, j, m_j), is **occupied by just one electron**. Then we have for a given n and $\ell > 0$ just the two possibilities $j = \ell \pm 1/2$ with $2j + 1$values for m_j, giving together $2(2\ell + 1)$ electrons.

In Pauli's words of his Nobel Prize lecture [7]:

> *"The complicated numbers of electrons in closed subgroups reduce to the simple number* ***one*** *if the division of the groups by giving the values of the 4 quantum numbers of an electron is carried so far that every degeneracy is removed. A single electron already occupies an entirely non-degenerate energy level."*

In his original paper Pauli enunciates his principle as follows:

> *"There can* ***never be two or more equivalent electrons*** *in an atom, for which in strong fields the values of all quantum numbers* n, ℓ, j, m_j *are the same. If an electron is present in the atom, for which these quantum numbers have definite values, this state is 'occupied'."*

From this Pauli deduces the numbers **2**, **8**, **18**, **32**,**...** of electrons in closed shells, and the **reduction of terms** for equivalent electrons. Several further applications are always in accordance with experience.

At the end of his paper Pauli expresses the hope that a deeper understanding of quantum mechanics might lead to a derivation of the exclusion principle from more fundamental hypothesis. To some extent this hope was fulfilled in the framework of relativistic quantum field theory. Pauli's key role in establishing the *spin-statistic theorem* is well-known (see, e.g., [11]).

Initially Pauli was not sure to what extent his exclusion principle would hold good. In a letter to Bohr of 12 December 1924 Pauli writes '*The conception, from which I start, is certainly nonsense. (...) However, I believe that what I am doing here is no greater nonsense than the hitherto existing interpretation of the complex structure. My nonsense is conjugate to the hitherto customary one.*' The exclusion principle was not immediately accepted, although it explained many facts of atomic physics. A few days after the letter to Bohr, Heisenberg wrote to Pauli on a postcard: '*Today I have read your new work, and it is certain that I am the one who rejoices most about it, not only because you push the swindle to an unimagined, giddy height (by introducing individual electrons with 4 degrees of freedom) and thereby have broken all hitherto existing records of which you have insulted me. (...).*'.

For the letters of Pauli on the exclusion principle, and the reactions of his influential colleagues, I refer to Vol. 1 of the *Pauli Correspondence*, edited by Karl von Meyenn [12]. Some passages are translated into English in the scientific biography [2] by Charles Enz.

4 Exclusion principle and the new quantum mechanics

On 26 August 1926, Dirac's paper containing the Fermi-Dirac distribution was communicated by R. Fowler to the Royal Society. This work was the basis of Fowler's *theory of white dwarfs*. I find it remarkable that the quantum statistics of identical spin-½ particles found its first application in astrophysics. Pauli's exclusion principle was independently applied to *statistical thermodynamics* by Fermi [4].

In the same year 1926, Pauli simplified Fermi's calculations, introducing the grand canonical ensemble into quantum statistics. As an application he studied the behavior of a gas in a magnetic field (paramagnetism).

Heisenberg and Dirac were the first who interpreted the exclusion principle in the context of Schrödinger's wave mechanics for systems of more than one particle. In these papers it was not yet clear how the spin had to be described in wave mechanics. (Heisenberg speaks of spin coordinates, but he does not say clearly what he means by this.) The definite formulation was soon provided by Pauli in a beautiful paper [14], in which he introduced his famous spin matrices.

At this point the foundations of non-relativistic quantum mechanics had been completed in definite form. For a lively discussion of the role of the exclusion principle in physics and chemistry from this foundational period, I refer once more to the address [1] of Ehrenfest.

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[4] According to Max Born, Pascual Jordan was actually the first who discovered what came to be known as the Fermi-Dirac statistics. Unfortunately, Born, who was editor of the *Zeitschrift für Physik*, put Jordans paper into his suitcase when he went for half a year to America in December of 1925, and forgot about it. For further details on this, I refer to the interesting article [13] by E. L. Schucking.

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Review of the Young Talent Day and Rudolf Clausius Symposium at EPFL, 8 October 2022

Antoine Pochelon, Evgenii Glushkov, Gernot Scheerer

As we just had chosen for our symposium the historical theme of Rudolf Clausius (1822-1888) for his role in the formalization of thermodynamics and as father of the concept of entropy, a tweet from EPFL president came to encourage us in our choice. He expressed his appreciation for an unusual and nicely surprising introduction to a recent article:

> *"If physical theories were people, thermodynamics would be the village witch. Over the course of three centuries, she smiled quietly as other theories rose and withered, surviving major revolutions in physics, like the advent of general relativity and quantum mechanics. The other theories find her somewhat odd, somehow different in nature from the rest, yet everyone comes to her for advice, and no one dares to contradict her." [1].*

The Swiss Physical Society invites every year the successful young participants to Swiss national and international science competitions to its Young Talents Day (YTD). Since the combination of history and modern research is particularly attractive to young people, the program of the day offered in the morning laboratory visits for selected students, and in the afternoon a symposium open to a larger public. The invited students are current year winners of the Swiss Physics Olympiad (SwissPhO), Physicists' Tournaments, Schweizer Jugend Forscht or similar competitions, which offers them the opportunity to visit research laboratories, receive first-hand information and feel the atmosphere of current research.

Arriving early morning from all parts of Switzerland to EPFL, the students were welcomed with coffee and croissants before a short introduction to the laboratory visits. Thanks to the cooperation with Prof. Giulia Tagliabue and Prof. Aleksandra Radenovic, the students had a chance to visit modern research laboratories involved in exploring new avenues for harvesting renewable energy. The eyes of the students were filled with enthusiasm and excitement, and their questions were often catching the guides by surprise. Seeing the laboratories so close and talking directly to researchers definitely sparked further enthusiasm in these bright young people, and that is exactly why we organize events like this one.


Fig 1. Opening of the YTD, Evgenii Glushkov introducing to the morning laboratory visits.

This public symposium, organized by the Swiss Physical Society, with the support of the Swiss Academy of Sciences SCNAT and EPFL was dedicated to the physicist and mathematician *Rudolf Clausius*, with several lectures dealing with his contribution to modern thermodynamics. Another part of talks was dedicated to physics tournaments at all ages. All talks can be found here: https://indico.cern.ch/event/1177925/ .

The choice of the speakers was rapid and allowed to cover, starting from the theme of Rudolf Clausius, different aspects of entropy, as the term and concept was invented by Clausius. The concept was developed along three axes in three talks. The first dealt with historical aspects, the second with entropy and life, and the third with entropy and smart use of energy. The historical part, covered by Jean-Philippe Ansermet, allowed the audience to discover local historical contributors to thermodynamics, namely Charles Soret (1854

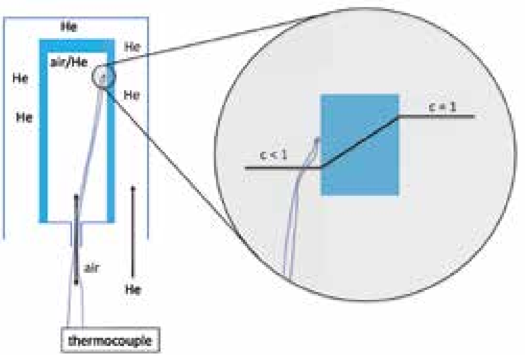

Fig 2: Jean-Philippe Ansermet demonstrating the Dufour effect, where a Helium concentration gradient in a porous wall induces a local temperature change at the thermocouple.

- 1904, Genève) and Charles Dufour (1832 Veytaux - 1902 Morges). The lecture was accompanied by experiments on thermophoresis [2], for example, a temperature gradient induces a concentration gradient (Soret effect). The reciprocal effect is more elusive, as shown in an original setup designed to bring this effect to the forth, namely, the fact that a concentration gradient induces a temperature gradient (Dufour effect), see Fig. 2. Dufour was professor in Lausanne and made experimental research in thermodynamics. He was member of the Société Vaudoise des Sciences Naturelles and of the ETHZ Council and refused to succeed to Clausius when Clausius left Zürich in 1855. A second presentation, by Paolo de Los Rios, with wonderful hand drawings and everyday examples, well accessible even to young people, described entropy in terms of order / disorder in the frame of biophysics and life. The third talk, by Daniel Favrat, was practically oriented on the efficient use of energy, distinguishing in energy a useful part, called exergy, the part corresponding to the maximum possible work in a process, and a part unable to do work, called anergy [2]. Clausius in fact defined the entropy as proportional to anergy.

Fig. 3. Paolo de Los Rios (left) and Daniel Favrat (right).

A second motivation of the symposium was to make physics tournaments better known in the public and schools. Emilie Hertig (by video from Cambridge, UK) and Florian Koch gave us an overview of tournaments at gymnasial level, the SYPT (Swiss Young Physics Tournament, for the age of 16-20) and at school level, the SYNT (Swiss Young Naturalists' Tournament, age 12-16), which could gain at being better known in Suisse Romande, see [3] for details. Note that this year was a golden year for the Swiss teams: the SYPT Swiss team won gold with the best place, the first team among 25 nations at the IYPT in Romania in 2022.

Evgenii Glushkov reported about tournaments at the university level with the IPT (International Physicists' Tournament) to be better known elsewhere than the two Swiss federal universities already involved - ETHZ and EPFL. The Swiss IPT team went into the finals and came out brilliantly 3rd of 15 teams at the international final in Colombia in May, 2022.

To interest the pupils, we contacted professors directly and through the Commission Romande de Physique (CRP) at their "Cours de Perfectionnement". Schools have also been contacted but it was clear that we need to spread information about such activities much earlier. That is a lesson for the organisers of the next editions: all the relevant entities should be informed a long time in advance to increase their involvement.

The general public was invited to attend the symposium's lectures, in addition to the YT. About the language used: most of the talks were thought to be given in French, but due to the presence of non-French speaking people in the audience, a general vote showed that a majority was rather demanding English. Thus, French appears no more possible, which some of us felt as a loss.

The students' travel between home and EPFL together with lunch were offered by the Swiss Physical Society and the Swiss Academy of Sciences (SCNAT). We would like to thank the EPFL Physics Section and Institute of Physics for sponsoring the venue and the aperitif, and the speakers for their exciting presentations. Special thanks goes to Jean-Philippe Ansermet for his support during the organization.

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Local physical societies

In view of organizing future events of that sort, especially in Suisse Romande, it would be useful and helpful that the SPS could collaborate with a local physics society, thus benefiting from its knowledge of the local context and possibilities, its network of people and organizational power, for example on the model of the collaboration between the PGZ (Physikalische Gesellschaft Zürich) and the SPS, see i.e. [4]. Unfortunately, the former AVCP (Association Vaudoise des Chercheurs de Physique) is no more active, so that other existing or new forces would be most welcome. A collaboration with such a local/regional group would undoubtedly be mutually beneficial.

The Physics of Music

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What is music? Since the answer depends on whom you ask, I feel free to provide my favorite definition: The core elements have to do with dancing (rhythm) and singing (melody). Music is rhythm, melody, or a combination of these two. There exist innumerable refinements involving polyphony, harmony, tonality, instrumentation, structure. Humans can make music, animals too, so do natural phenomena and inanimate objects. Certain aspects involve human creativity or – for the spiritually inclined among us – divine inspiration, for other aspects we all agree that these follow the laws of physics. Obviously, the latter is the core material of courses on physics of music [1,2]. However, the former is what beauty is about, and it would be a sin to omit it. This makes preparing and giving courses in physics of music such a great adventure. The subject invites teachers and students to delve in a goldmine of subjects involving history, linguistics, religion, music, anatomy and physics.

I start by summarizing a few essential points about music and tonal intervals. Melodies sung or played on an instrument are sequences of tones distributed along a musical scale. An example of such a scale is the sequence of 8 white keys on a piano keyboard starting at the central **c**: **c-d-e-f-g-a-b-C**. The 8th tone (**C**) has twice the frequency of the first one (**c**), and after the **C** the series continues with the other – also frequency doubled – tones. Not all these tone intervals are equal: The frequency ratios **d:c**, **e:d**, **g:f**, **a:g** and **b:a** are approximately 1.12 (a "whole-tone interval"), whereas **f:e** and **C:b** are approximately 1.06 (a "semitone interval"). Since two different tonal intervals are used, the scale is called "diatonic", and in this example the sequence of intervals is 1.12, 1.12, 1.06, 1.12, 1,12, 1,12, 1.06. We call this sequence the "Ionian mode". If we start at the **a**, and we play again only the white keys, the sequence of intervals becomes 1.12, 1.06, 1.12, 1.12, 1.06, 1.12, 1.12. We call the latter sequence the "Aeolian mode". We see that the pattern of intervals is different from the Ionian mode. Of course, if we sing, we are not confined to the tones imposed by the keys of a piano, and thus we could equally well sing the Aeolian mode starting from any other tone than the **a**, including the **c**. Since the Ionian and Aeolian sequences differ from each other, we now have 2 sequences starting from the **c**, each sounding differently. As a next step we could adopt a different order of the notes, for example we play or sing something like **g-g-g-C-C-b-b-g-g-g-D-D-C-C**. These are the tones of the first strophe of a sunny song that some of you will recognize. If we transpose it down in the same way as we did for the scale of **c**, and once again play only the white keys, we get **e-e-e-a-a-g-g-e-e-e-b-b-a-a**, sounding a little less sunny, let's say a bit more melancholic. These two different ways to set this melody represent two different "modes" as it is called in music theory. Modes have been used since antiquity: heptatonic modes such as the two examples above, and also pentatonic modes. Mesopotamians distinguished in the beginning of the second millennium BCE seven heptatonic modes [3], which they called *Išartu*, *Kitmu*, *Embūbu*, *Pūtu*, *Nīd qabli*, *Nīš gabarî* and *Qablītu* [4]. The ancient Greeks rebaptized this using the names of the regions where these modes were most commonly used, from which we inherited the denominations Ionian, Dorian, Phrygian, Lydian, Mixolydian, Aeolian and Loerian that are still in use today. Regardless as to whether your taste is for classical, religious or popular music, if you regularly listen to music or play or sing it yourself, you are frequently exposed to any one of these seven modes.

In the above description I gave the values ~1.06 and ~1.12, which are only approximate. In practice one doesn't sing these intervals. A singer automatically tunes to natural intervals, i.e. (s)he adjusts one frequency (f_1) to another one (f_2) such that the ratio $f_1 : f_2 = h : j$ where h and j are integer numbers. How come? Superimposing the sound of two frequencies produces beats of the sound amplitude, beating at the difference frequency. Most humans perceive a beat frequency higher than 2 to 4 per second as unpleasant, and a slower beating as acceptable. A natural consequence is that musicians tune the frequencies they sing such, as to eliminate beating as much as they can. Comparing two frequencies, this requires that their ratio is given by $h : j$ where h and j are integers. This practice is called "just intonation". If people sing different musical lines at the same time while respecting just intonation, the harmonies resulting from this polyphony are very pleasing to the ear. Depending on the structure of the melody there may be some peculiar consequences. The perfect harmonies force the tuning in the course of certain sequences to increase or decrease by one or several tiny intervals known as "syntonic commas" (about ¼ of a chromatic semitone interval) first described by ***Didymus the Musician*** in the first century CE [5]. ***Giambattista Benedetti*** (1530 - 1590), a mathematician with an interest in physics and the science of music, wrote a musical composition to demonstrate this tonal migration effect [6]. ***Michaelangelo Rossi*** (1601 - 1656), composer, violinist and organist recognized that tonal migration is a real problem for an ensemble of good singers using just intonation. Performing his madrigal "Per non mi dir" from beginning to end one accumulates an overall migration of 11 syntonic commas (about 3 semitones!). Rossi organized courses specifically to instruct choirs how to avoid this problem. A very instructive discussion about this is offered by ***Elam Rotem*** – contemporary composer, singer and harpsichord player based in Basel – on his youtube channel Early Music Sources [7].

Among physicists one finds – just as in any other sector of society – music lovers: people who play an instrument, who sing, who have studied music on some level, from elementary to professional. The possession of an analytically gifted mind does not exclude having an artistic side as well. Good scientists are creative, and creativity finds many different outlets. In the history of science, one finds many scientists who had a dual career in science and music. To illustrate this, I will describe below how the physics of music has evolved throughout the history of mankind.

The first scientific research on this subject is traditionally attributed to ***Pythagoras*** (570 - 495 BCE). Pythagoras used a monochord, an instrument already mentioned in Sumerian texts, to establish that the ratio 1:2 of the wavelength of a vibrating string corresponds to an octave (in modern termi-

Figure 1. Pythagoras doing experiments with various different instruments. Woodcut [8].

nology), and the ratios 3:2 and 4:3 to a fifth and a fourth respectively [8] (see Fig. 1). ***Plato*** (423 - 348 BCE) appeals in the Socratic dialogue Timaeus to the notions of ἐπόγδοον (“greater by an eighth part”) and λεῖμμα (“residue”). The former he identified as the ratio 9:8, an interval which we call nowadays “major second”, the latter as 256:243, corresponding to “minor second” in contemporary terminology. Much later ***Marin Mersenne*** (1588 - 1648), ordained Catholic priest and polymath, developed the laws describing the harmonics of a vibrating string. His seminal work on music theory, “Harmonie universelle”, earned him the epithet "father of acoustics". Returning to antiquity ***Aristoxenos*** (360 - 300 BCE) treated in “Aristoxenou Harmonika Stoicheia” the nature of musical intervals and scales. Unlike Pythagoras, Plato and Aristotle, who considered music in the context of cosmology and ethics, Aristoxenus examined the tonal structure of music as a system in itself and studied the relationship between notes “as multiples of a particular unit of measurement… for example, the interval of a fifth as three and a half tones without reference to the ratio of 3:2 and in this way it is more compatible with the way that the human mind perceives music.” [9] ***Klaudios Ptolemeos*** from Alexandria (100 - 170) based tonal intervals on arithmetic ratios backed up by empirical observation, and he proposed various different ways to divide the octave. His book “Harmonikon” where he described all this – and more – had quite an impact: Even fourteen centuries later ***Gioseffo Zarlino*** (1517 - 1590) considered Ptolemy's “intense diatonic scale” the only tuning that could be reasonably sung. ***Christiaan Huygens*** (1629 - 1695) applied logarithms, right after the mathematics of logarithms had been introduced, to advance the understanding of musical scales and for the development of equal temperament. ***Johannes Kepler***, ***Nicolaus Mercator***, ***Isaac Newton***, ***René Descartes***, ***Jost Bürgi*** all worked on the division of the octave [10,11]. Descartes and Bürgi used diagrams bearing a striking resemblance to the “volvelles” (circular wheel charts) that had been used by astronomers since the Middle Ages. To be specific, they used the circle as a metaphor for the octave in combination with a logarithmic representation of musical ratios [12]. ***Leonhard Euler*** (1707 - 1783) described in “Tentamen novae theoriae musicae” [13] a conceptual lattice diagram representing tonal space (the “Speculum musicum”, see Fig. 2), which in the 19th century drew renewed interest as the “Tonnetz” in neo-Riemannian mathematics of music (after ***Hugo Riemann***, not to be confused with the more famous Bernhard Riemann). ***Thomas Young*** (1773 - 1829) “the last man who knew everything” busied himself with inventing the double-slit experiment named after him, Young's modulus, astigmatism, functioning of heart and arteries, a grammatical comparison and vocabulary of 400 languages, and deciphering Egyptian hieroglyphs, in particular the Rosetta stone. He also invented a temperament, i.e. a subdivision of the octave, that has been used and appreciated by composers and musicians throughout the 19th century. In the beginning of the 20th century Young’s temperament got – much undeservedly – abandoned under the influence of the mass production of pianos, and ever since mankind has been systematically brainwashed with equal temperament [14,15]. ***Hermann von Helmholtz*** (1821 - 1894) developed a mathematical theory to explain the timbre by overtones. He described this theory in “Die Lehre von den Tonempfindungen als Physiologische Grundlage für die Theorie der Musik”, a classic in the literature of science of music [16]. ***Adriaan Fokker*** (1887 - 1972) was a theoretical physicist. He also introduced a new method (the “Fokker periodicity block”) to relate musical intervals in just intonation to those in equal tuning, designed and built keyboard instruments capable of playing microtonal scales via a generalized keyboard, among which an organ which has 31 tones in the octave for which he also composed music.

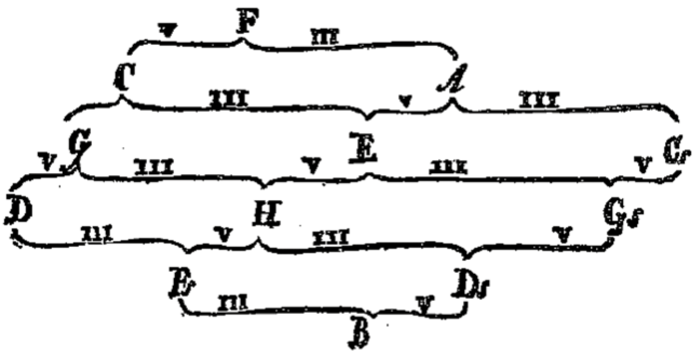

*Figure 2. Leonhard Euler's Tonnetz [10] showing the triadic relationships between the perfect fifth, major third and minor third. The **f** is on top, left below it the **c** (**c**:**f** = 3:2, a perfect fifth), and to the right the **a** (**a**:**f** = 5:4, a major third). The ratio **a**:**c** is then 5:6, corresponding to a minor third. These arithmetic relations are repeated along the vertical and horizontal directions of the graph.*

Why should we care about the interface of music and science? Students. They are openminded, they are curious. And they may, just may, get the totally peculiar impression that physics is only about equations and numbers. Which might be perceived by some of these inquisitive minds as boring, as unjustified as that may sound to matured physicists such as many of us are. And unjustified this impression is. Many of us have the privilege of doing curiosity driven research, and usually we find our own most recent scientific result the most interesting of all. Editorial boards of high-profile journals bear the burden of our enthusiasm in the form of an incessant deluge of submissions reporting – as it was so aptly formulated by the late professor ***Cor Haas*** (1930 - 2019) – "a negligible correction to an unobservable effect". However, if you place yourself in the position of an adolescent, would you be really attracted by the scientific research that you are presently doing? For certain subjects it may be love at first sight, but we shouldn't forget that for many of the subjects on which we presently work it took us some time to perceive the beauty of it.

That said, the subject of physics of music appeals quite readily to peoples' imagination. How do I know? Experience. I give two of the many possible examples:

Example 1. This morning (29 December) I interrupted my frantic writing of this article to beat the 31 December deadline for a cup of coffee, and looked at today's newspaper. There it was: A photo filling half the frontpage with the header: Arithmetique de l'accoustique, accompanied by a long and interesting article on page 9 explaining that two tones played simultaneously on a violin (called "dyade") produce a difference tone that is audible to the human ear, also of non-experts. The effect is quite distinct in ancient instruments; the Italian composer ***Giuseppe Tartini*** discussed it in 1714. This effect is not noticeable in modern violins [17,18].

Example 2. In the past 5 years I've given modules of "physique de la musique" as part of a full-year course "physique du quotidien" of my colleague Andreas Müller at the Department of Physics of the University of Geneva [19]. In 2021 this was attended by an auditor, Eric Rey, who contacted me after my course with the proposal to mount a public lecture together with him and the other four members of Geneva Brass. I said "yes", worked hard, and so did the 5 professional musicians of Geneva Brass. That said, we weren't so sure if anyone would show up for our conference-concert "la Physique Résonne" on a rainy evening in early November [20]. The auditorium had place for 300. It turned out to be not big enough, people were sitting on the stairs. During 90 minutes musical interventions and demonstrations played by the brass quintet alternated with explanations by me on questions such as: What is a resonance? How does sound travel through air? How is the sound produced by a wind instrument defined by its shape? What makes a chord consonant or dissonant? Why can a piano or an organ only be out of tune? Is the pitch of the alphorn higher or lower at the top of the Matterhorn than down below in the valley? (see Fig. 3) And how does that change at the North Pole, in the Sahara, or on Mars? The audience, consisting of non-experts in physics and music, loved it. Why? My understanding is, that the subject appeals to seemingly antagonistic aspects of the human mind, namely the analytical and the artistic, and that is intriguing.

Figure 3. Christophe Sturzenegger (Geneva Brass) playing alphorn at the summit of Dent Blanche (left, 4356 m) and in Crans-Montana (right, 1495 m)

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Hybrid Energy Systems

Bernhard Braunecker

The security of gas and electricity supply in Switzerland is currently and perhaps also in the next years at the center of public discussions. Pragmatic solutions that can be quickly implemented are demanded, and any conflicts with binding climate agreements are being verbally downplayed, as the aim is to find only interim solutions. This is politically understandable in view of the increasing public nervousness, but any intermediate concept should always be expandable to new sustainable solutions in the future.

One example is the gas-fired power plant, which has so far been frowned upon as a representative of fossil technology, but has good political chances of realization in the short term due to its undeniable positive features as will be shown. Its main disadvantages, such as the uncertain gas supply situation, the significant increase in gas prices and the unavoidable CO_2 emissions are accepted as lesser evils for the moment.

If the decision for gas-fired power plants once has been done, why not incorporate it into long-term strategies to avoid losing investment efforts and acquired know-how? Couldn't we consider scenarios that neutralize the disadvantages mentioned? Physicists know that inside a closed system problems can always be overcome by combining it with other systems to create new degrees of freedom. These so-called hybrid systems should not only add up the advantages of each subsystem, but also compensate for each other's disadvantages in the right way. To this end, we present next some suggestions: First, we describe the combination of gas power generators and CO_2-extraction systems, and secondly, we mention small nuclear power plants as central energy source for interesting application cases.

Modern combustion approaches

One interesting type of gas-fired power plants currently in discussion in Switzerland are modern Combined Cycle Gas Turbine power plants CCGT (Fig. 1)[1]. They are technically mature, have a high efficiency, are commercially available at short notice and can be well integrated into existing local infrastructures[2].
In the working range from 0.1 to 40 MW, they can be ramped up to full load within a few minutes and thus can compensate for the power fluctuations of renewable energy sources, a first interesting hybrid approach. Different CCGT variants up to about 350 MW exist as well, but are more intended for continuous operation.

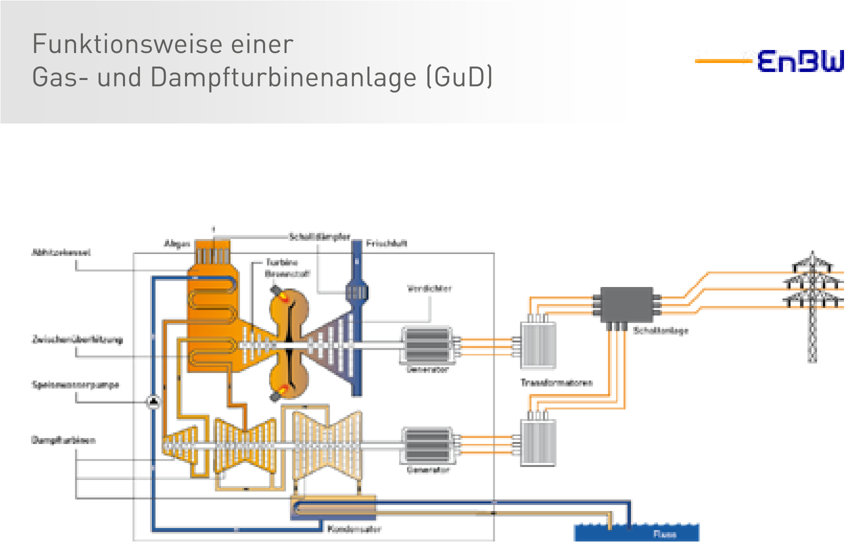

Fig. 1: Schematic of a CCGT (from [2])

Gas-fired power plants are attractively priced: The Swiss Federal Office for Energy BFE quotes an investment sum of 800 ± 100 MCHF for 1 GW of generated power output[3]; other estimates assume 600 - 800 MCHF / GW. In both cases, one arrives at about 240 MCHF for a 300 MW plant. Operating costs are reported to be 8 MCHF / a, but the main problem is the gas price. Since they varied in 2022 between 27.33 and 70.04 USD / MMBtu[4], which corresponds to 83.8 and 214.8 CHF / MWh, then for a 300 MW plant, producing 2.68 TWh / a, the gas costs would be between 220 and 565 MCHF / a[5].

The uncertainty of gas supplies is a disadvantage, as Switzerland is dependent on imports of gas, most of which came until now from Russia. However, as this affects all European countries and new supply scenarios based on Liquefied Natural Gas (LNG) are being intensively promoted throughout Europe, the problem probably will become of minor importance already in the medium term. In addition, important gas pipelines between the northern EU states and Italy already run through Switzerland, so that the physical access to LNG flows is guaranteed, regardless from which direction the gas would come, provided the political conditions are right. On the other hand, the CO_2 emission of the CCGTs is not ignorable, even if the specific emission with $K_{CCGT} = 0.4\ t_{CO2}$ / MWh is already significantly improved compared to a 'normal' coal-fired power plant with 1 t_{CO2} / MWh[6].

In Switzerland eight mobile gasturbines TM2500 from General Electric are currently installed in Birr (AG) as emergency generators for power shortages. They should deliver 250 MW, and their CO_2 emission in 14 days is 50'750 t_{CO2}[7].

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[1] The 'combined cycle gas turbine' (CCGT) is a two-step machine; first the hot gases drive a gas turbine and second, the still hot exhaust gases produce steam for running a steam turbine. https://en.wikipedia.org/wiki/Combined_cycle_power_plant

[2] https://www.enbw.com/energie-entdecken/energieerzeugung/konventionelle-erzeugung/

[3] https://www.bfe.admin.ch/bfe/de/home/news-und-medien/medienmitteilungen/mm-test.msg-id-90735.html

[4] https://ycharts.com/indicators/europe_natural_gas_price

[5] The gas price in December 2022 was about 189 Euro/MWh in Switzerland.

[6] https://de.statista.com/statistik/daten/studie/38910/umfrage/hoehe-der-co2-emissionen-nach-kraftwerk/

[7] Faktenblatt Reservekraftwerk Birr: https://www.bfe.admin.ch/bfe/de/

This corresponds to $K_{Birr} = 0.6\ t_{CO2}$ / MWh. But the installation is clearly intended as reserve power plant to be run only in exceptional situations, and climate-neutral operation through the use of CO_2-free fuels is required.

CO_2 extraction parks

This disadvantage of a CCGT could be reduced or even eliminated in the long term if the emitted CO_2 is removed out of the air and physically and/or chemically bound, as envisaged by the ***Orca*** aggregates (Fig. 2) of the company ClimeWorks [8]. One could install several of these aggregates in corresponding CO_2 extractions parks near to the CO_2 emitters, in analogy to the wind parks with their fleet of wind turbines for electricity generation. It would also be thinkable to minimize installation and service costs by combining wind and CO_2 extraction modules in a common park outside agglomerations as another attractive hybrid approach.

Fig. 2: Orca extraction modules of ClimeWorks (from [8])

Here is an estimate: An Orca binds $4 \cdot 10^3\ t_{CO2}$ / a [9] at a power input of 1 MW. Its characteristic CO_2-extraction factor is therefore $K_{Orca} = 4 \cdot 10^3\ t_{CO2}$ / MWa ~ $0.4\ t_{CO2}$ / MWh [10] [11]. It can be seen that K_{Orca} is equal to the mentioned emission factor of a CCGT with $K_{CCGT} = 0.4\ t_{CO2}$ / MWh. This means that the total CCGT power produced would be consumed by the Orcas to sequester the CO_2 emissions of the CCGT, thus still a meaningless zero-sum game.

If, however, one would succeed to halve the CO_2 emissions of the CCGTs and to double the CO_2 binding capacity of the Orcas, neither of which seems to be unrealistic, one would have an attractive variant with this hybrid approach. Then a CCGT of 300 MW would generate $300\ \text{MW} \cdot 1/2 \cdot 4 \cdot 10^3\ t_{CO2}$ / MWa = $6 \cdot 10^5\ t_{CO2}$ / a, which can be bound by $N_{Orca} \cdot 2 \cdot 4 \cdot 10^3\ t_{CO2}$ / a, i.e. by $N_{Orca} = 75$ Orcas.

If, in addition, technical improvements allow reducing the power requirement from 1 MW to 0.5 MW per Orca, the CO_2 park would need only 37.5 MW operating power, which is 12.5 % of the 300 MW generated by the CCGT. And if one further succeeds to lower the price from the current 10 MCHF to 1 MCHF per Orca by larger production numbers, then the resulting investment costs of 75 MCHF would be in a reasonable proportion to the already mentioned investment costs of 240 MCHF for a 300 MW CCGT. However as already mentioned the actual gas costs are the main problem.

Modern nuclear approaches

Modern nuclear technology also offers attractive solutions in which considerable progress has been made in terms of economic efficiency and operational safety. Especially interesting for future applications are Small Modular Reactors (SMR), where according to [12] more than 80 designs are under development and deployment in 18 states. Further detailed information about SMRs can be found in [13]. Here we mention General Atomics' Energy Multiplier Module EM^2 (Fig. 3), a modular, grid-connected energy source with a net block power of 265 MW [14]. EM^2 is a helium-cooled reactor with a core exit temperature of 850°C. The reactor uses a "convert-and-burn" core design in which the fuel used is converted internally into fissile isotopes. A refill of fuel is required only every 30 years. The reactor is housed in a sealed containment below the bottom and is equipped with advanced passive safety methods to control heat removal and reactivity. EM^2 also uses a closed-cycle direct gas turbine to increase efficiency [15]. This impressing module shows a further advantage of modern nuclear concepts when comparing its generated power density factor of 10 kW/m^2 with 5 W/m^2 of solar- and 2 W/m^2 of wind technology [16].

Fig. 3: EM^2 System of General Atomics (from [13])

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[9] An Orca aggregate consists of eight collector containers with an annual capture capacity of 500 tons each.

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eVinci™ Micro Reactor (Westinghouse) *

The eVinci™ micro reactor's design is based on space reactor technologies and best suited for energy consumers in remote locations. Due to its small size the reactor is transported by special flat-bed trucks. Modern heat pipe technology is used to extract the core heat. According to the manufacturer the key attributes are:

- Transportable energy generator
- Fully factory built, fueled and assembled
- Delivers combined heat and power – 5 MWe and up to 13MWt
- 8+ years of full power operation prior to refueling
- Target less than 30 days onsite installation
- High speed load following capability
- High reliability and minimal moving parts
- Capable of autonomous operation
- Near zero Emergency Planning Zone with small site footprint
- No spent fuel or waste storage on site
- Simplified decommissioning and remediation

* https://www.westinghousenuclear.com/energy-systems/evinci-micro-reactor

FMR in local hybrid plants

At the same time Fast Modular Reactors (FMR), i.e. micro-reactors of only about 10 - 50 MW, are in development. The FMR of General Atomics of 50 MW (see page 193 in [12]) is expected to demonstrate reactor operation before 2030. These modern aggregates with their closed gas cooling circuits are further developments of the modules used in submarines, and they are foreseen for space applications, especially also for space nuclear propulsion. Here we mention the micro reactor eVinci from Westinghouse (see Box) with a technology and manufacturing readiness level of 5, where one expects nuclear demonstration in 2024 (see page 349 in [12]).

As turnkey, small-volume and user-friendly reactors, they are ideally suited as autonomous energy modules in remote agglomerations in third world countries. They would not only ensure the supply of electricity for daily use at a modern level, but could also be used for the desalination of seawater and for the production of hydrogen as a propellant or for the cooling of large food halls. Another argument in their favor is that many regions in third world countries suffer from increasingly frequent catastrophes such as tornadoes and major floods, which usually paralyze the supply chains to many villages for a long time due to destroyed power lines. Autonomous FMRs, which are installed underground, are largely immune to this type of disruption.

Fig 4: Westinghouse's vision of the mobile micro reactor eVinci.

Finally, it would be worth considering installing the above-mentioned CO_2 extraction parks as stand-alone plants in regions remote from civilization. Then an autonomous FMR of 40 MW would be a small volume, easy to install and maintenance-friendly energy source for such a novel park concept [17].

More global thinking in Switzerland

Switzerland, with its approximately eight million inhabitants, represents about 1 per mille of the world's population. It therefore contributes de-facto more or less about this small factor to the world's climate and environmental crises, but the same also holds for all the national efforts to mitigate the crises, such as reducing CO_2 emissions. It may therefore be asked, if the big financial means to substitute the combustion engine of all Swiss cars by an electric unit should not be better invested in new hybrid technologies that would allow billions of people in Africa, Asia and South America to improve their life quality? If new energy concepts could cause them to stop the burning of wood and coal, then the effect on the global environment would be much stronger than any national Swiss action. Switzerland has the necessary expertise in research and in industry and is part of many international networks. This strong competence would allow to transfer new hybrid technologies into mass products that would be affordable for third world countries.

Outlook

The global climate crisis and the shortage of energy supply cannot be solved by appeals for savings alone; what is needed are technical solutions whose advantages are accepted without hesitation. Hybrid approaches that combine the features of different technologies, so that the new system is more efficient, more flexible, more cost-effective and more easy to use than the individual subsystems, require high engineering competence. Switzerland could offer this to the world in order to solve the global problems there where the majority of them arises. If the living conditions of the population in third world countries can be improved at the same time, other crises triggered by the emigration flows of disillusioned people would hopefully also be significantly defused.

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[17] Idea of Rodrigo Braunecker-Sicilia (14 years old)

International recognition of Jost Bürgi (1552 – 1632)

Jost Schmid-Lanter, Zentralbibliothek Zürich

Peter Fux (left) and Jost Schmid-Lanter unveiling the entrance to the Jost Bürgi Research Library.

One of the historically most interesting 'triple constellations' was the collaboration of the German Johannes Kepler, the Dane Tycho Brahe and the Swiss Jost Bürgi around 1600 in Prague at the court of Emperor Rudolf II. Kepler could not quantitatively explain the measured data of planetary motions around the Sun provided by Brahe and Bürgi using the approach of circular orbital curves, which could be due to measurement inaccuracies as well as to his theoretical approach. When the discrepancy could not be resolved even with Bürgi's more accurate time and angle measuring instruments, Kepler replaced the circular orbits first with ovals, then with elliptical orbits, and now found much better agreement between theory and experiment. The new approach enabled him to derive further laws of planetary motion, which entered the history of modern science as Kepler's three laws, and whose date of formulation is considered by many to be the beginning of modern astronomy.

The Jost Bürgi Initiative in Lichtensteig in the canton of St. Gallen, Bürgi's birthplace, has been endeavoring for some years to give Bürgi's person the historical appreciation to which he is entitled by organizing an annual international symposium in which the Swiss Physical Society participates from the beginning in 2015. The symposia were and are followed closely also in the USA.

The clocks and mechanical drives of celestial globes built by Bürgi were far ahead of their time due to technical innovations such as improved regularity of tooth pitch and shape and mastered assembly techniques of axle bearing and balancing. His instruments allowed to reliably measure time- and arc seconds, one strong reason to consider Bürgi as an early grand master of the art of watchmaking, the synonym for Swiss excellence.

New Jost Bürgi Research Library in New York

Probably the most important private library on the art of watchmaking was donated to the Horological Society of New York (HSNY) by Fortunat Mueller-Maerki on the occasion of last year's symposium of the National Association of Watch and Clock Collectors on 20-21 October 2022 in New York and made publicly accessible.

Fortunat Mueller-Maerki emigrated with his family to the USA at a young age, where he soon became a partner for the international executive search firm Egon Zehnder and set up the office in New York. As an "exiled Swiss", however, he returned to our country again and again, especially to the International Jost Bürgi Symposium. The lasting impression of this event and the contacts it created were one of the reasons why Mueller-Maerki christened his collection the "Jost Bürgi Research Library". The library contains some 25,000 cataloged items, making it one of the largest and most important specialized libraries on the art of watchmaking in the world. An already online catalog is currently being converted into an exchangeable format by the helpful and academic library staff of HSNY: bhm search (http://www.hsn161.com/BHM/bhm1-allusers/bhm_entry.php).

The Watch Library Reading Room and collections are located on the 5th floor of the General Society of Mechanics and Tradesmen building, 20 West 44th Street, New York City. The 100+ years old building contains (in the middle of Midtown Manhattan) an impressive multi-story auditorium framed by several galleries for exhibitions and other General Society library collections. The core team of the Jost Bürgi Initiative was invited to the ceremonial naming of the "Jost Bürgi Research Library". The team delegated Dr. Peter Fux and Dr. Jost Schmid-Lanter to this event to present Jost Bürgi and his work and to give an outlook on the upcoming large special exhibition (autumn 2023) on Bürgi in the Museum of Culture St. Gallen.

During the numerous meetings, important relationships were established and information was gathered: For example, that the work of the recently deceased graphic artist John Redfern can now be studied collectively. Due to copyright regulations, his ingeniously animated explanatory videos on watchmaking could only be seen in individual museums, and his person was previously known to only a few: https://redfernanimation.com/animations/

The US-American Mark Frank recently had an "Astro-skeleton" clock with 64 (!) complications built at his own expense and for private purposes. Apparently he also used Bürgi innovations for this purpose: http://www.my-time-machines.net/

Spin Qubit 5, Pontresina, Switzerland

Dr. Natalia Ares, University of Oxford