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Photo: © Manfred Richter

Annual Meeting of the Swiss Physical Society

29 June - 3 July 2020, Université de Fribourg

in collaboration with
CHIPP, SGN, PGZ, SCNAT,
Département de Physique - Université de Fribourg

Call for Abstracts: Submission Deadline 7 March 2020

More information on page 4.

The artist's view shows the hot Jupiter exoplanet 51 Pegasi b, the first exoplanet around a normal star found in 1995. The Nobel Prize 2019 acknowledges this important discovery by Michel Mayor and Didier Queloz (p. 9).
Picture © ESO / M. Kornmesser / Nick Risinger (skysurvey.org)

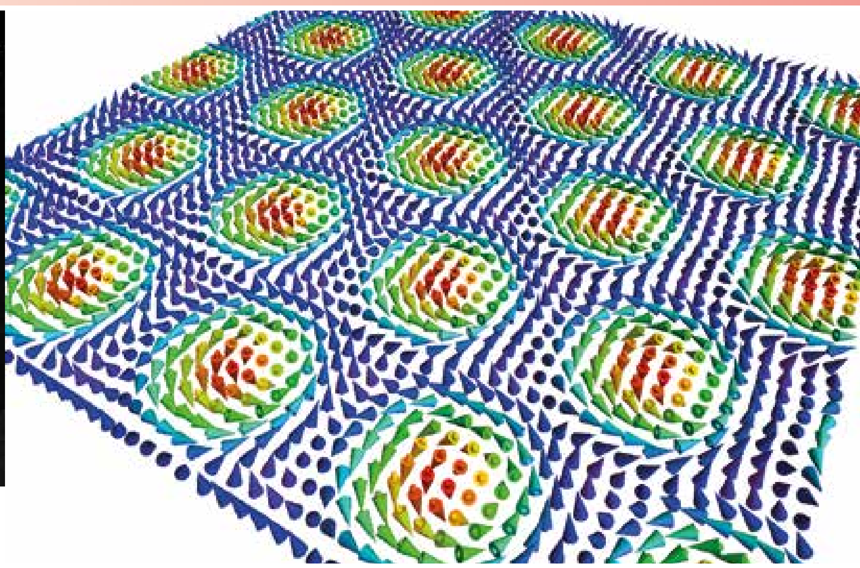

Illustration of the magnetization pattern in a triangular lattice of Bloch skyrmions. More on the fascinating field of skyrmions on p. 19. *Picture © Yoichi Nii*

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satw it's all about technology

Editorial

Der Weg zu immer kleineren Wellenlängen

Bernhard Braunecker

Viele der uns vertrauten Alltagstechnologien wie zum Beispiel die Objekterfassung im Strassenverkehr durch Radarsensoren im Auto basieren auf der Mikrowellentechnik. Aber auch die von Satelliten aus vorgenommene Erdbeobachtung mittels ‚Side-Looking Radar' sowie die Datenweitergabe zur Erde erfolgt durch Mikrowellen. Wir finden weiter Mikrowellentechnik in der Medizin oder bei der Teilchenbeschleunigung in Grossanlagen. Der Hauptgrund für die grosse Applikationsbreite ist die technisch beherrschte Phasenkonstanz der Sender. Um zum Beispiel eine Gegend mit Radar abzuscannen, muss die Antenne nicht mehr wie früher mechanisch gedreht werden, sondern man schaltet nur noch die Phasen nebeneinander angeordneter Sender/ Empfänger (Phased Array Prinzip).

Man erkannte aber auch frühzeitig, dass sich viele dieser technischen Leistungen deutlich steigern lassen würden, wenn man zu höheren Frequenzen und somit zu entsprechend grösseren Bandbreiten käme, wenn man also optische Systeme verwenden würde. Man wusste bereits seit Ernst Abbe (1840-1905), dass die eine Abbildungsoptik charakterisierende Anzahl auflösbarer Punkte im Gesichtsfeld eine informationstechnische Angabe ist, nämlich ein Ortsbandbreiteprodukt. Aber es dauerte doch bis Mitte des letzten Jahrhunderts, bis es gelang, optische Systeme in völliger Analogie zur elektronischen Nachrichtenübertragung informationstheoretisch zu beschreiben. Das holte die Optik endgültig aus der Nische der ausschliesslichen Objektabbildung heraus, und es zeichneten sich ungeahnte neue Möglichkeiten der Erfassung, Bearbeitung und Übertragung grosser Datenmengen ab. Nur konnte man damals diese Leistungen nicht abrufen, da keine geeigneten Lichtquellen als Sender zur Verfügung standen.

Also schielten die Optiker neidvoll zu den erfolgreichen Mikrowellentechnikern, um zu sehen, wie die es besser machten? Das war die Situation kurz nach dem 2. Weltkrieg. Erste Adresse waren damals die Bell Telephone Laboratories in USA. Dort arbeitete man intensiv an der Verbesserung der Radarauflösung und suchte nach geeigneten leistungsstarken und rauscharmen Mikrowellensendern. Der Physiker Charles H. Townes setzte in den 1950er Jahren die Einsteinsche Idee der stimulierten Emission um, indem er Ammoniakgas mit Mikrowellen der Frequenz von 24 GHz anregte, wobei der metallische Gasbehälter als Resonator diente. Zusammen mit seinem Schwager Arthur L. Schawlow wandten sie dieses *Maser*-Prinzip in den darauf folgenden Jahren auf kurzwelliges IR-Licht an, wobei der Resonator aus zwei Spiegeln gebildet wurde, und der *Laser* war geboren. Für seine bahnbrechenden Erkenntnisse bekam Townes 1964 den Nobelpreis in Physik. Als den Tag der ersten Inbetriebnahme eines Lasers einigte man sich in der Folge dann auf den 16. Mai 1960, als wiederum ein Physiker bei Bell Labs, diesmal Theodore Maiman den ersten Rubin Laser vorführte. Das löste einen schier unglaublichen Technologieschub bis heute aus, so dass man das 21. Jahrhundert mittlerweile als das Jahrhundert des Photons bezeichnet.

Der Erfolg der modernen Lichtwissenschaft bewog deshalb die UNESCO im Jahr 2015, ein Jahr des Lichtes auszurufen und weltweit zu Aktionen mit und über Licht anzuregen. Die sehr grosse Resonanz in der Öffentlichkeit ermutigte sie, nun alljährlich einen Internationalen Tag des Lichtes IDL zu veranstalten, und als Datum wurde sinnvollerweise der 16. Mai gewählt. Dieses Jahr feiert man daher das 60-jährige Laser-Jubiläum, und da dieser Tag zudem auf einen Samstag fällt, bietet sich für Institute, Firmen, Schulen, Gallerien etc. die grosse Chance an, die Öffentlichkeit zu Veranstaltungen über und mit Licht zu gewinnen (siehe Seite 39).

Dank der Verlässlichkeit der Laser konnte man nun vieles aus der Mikrowellentechnik mit deutlich besseren Leistungswerten übernehmen. So wurden aus Radar- nun Lidarsensoren mit höherer räumlicher und zeitlicher Auflösung; der zukünftige Datenverkehr zwischen Satelliten erfolgt zunehmend mit Laserlicht mit ungleich kleineren und leichteren Systemen, aber deutlich höheren Datenraten und geringerer Störanfälligkeit.

Und man arbeitet intensiv an optischen Teilchenbeschleunigern, die eines Tages zu kleineren Baulängen führen sollten. Das wäre auch deshalb wichtig, da Beschleuniger immer mehr auch als Strahlungsquellen im Röntgen- und Gammabereich verwendet werden, siehe den Swiss FEL. Mit kohärenter Röntgenstrahlung aus handlichen Anlagen, die dann im Gegensatz zu heute beim Anwender stünden, könnte man wiederum all die optischen Anwendungen verbessern wie z. B. in der Halbleiter-Lithographie, aber auch in der Medizin mittels neuartiger Phasenkontrastmethoden bei der Diagnostik und der Therapie von Tumoren. Der Trend zur kurzwelligen Röntgen-Photonik zeichnet sich ab und erfordert die Entwicklung neuer Konzepte und Materialen für Optiken, Beschichtungen und Sensoren.

Es ist deshalb mehr als angebracht, sich an *Wilhelm Conrad Röntgen* (1845-1923) zu erinnern, der 1895, also vor 125 Jahren, die nach ihm benannten Strahlen entdeckte und dessen Geburtstag sich zudem dieses Jahr zum 175. Mal jährt. Er hat von 1865-1868 am ‚Poly' in Zürich, der späteren ETH, studiert und diplomiert, sodann 1869 an der Uni Zürich bei August Kundt promoviert, bevor er seine Karriere in Strassburg, Giessen, Würzburg und München fortsetzte.

Ähnlich dem letztjährigen "150 Jahre Periodensystem" erinnern wir mit einem Symposium im Rahmen der SPG Jahrestagung an diesen grossen Physiker. In drei Vorträgen wird die Biographie Röntgens, die Geschichte der Röntgenstrahlung und der heutige Stand in der Forschung und in der industriellen Praxis beleuchtet werden (siehe Seite 6).

Annual Meeting in Fribourg, 29 June - 3 July 2020

The next annual meeting will take place from 29 June to 3 July 2020 at the Université de Fribourg. Renowned invited speakers will give plenary talks during each of the morning sessions, topical parallel sessions will allow in depth discussions during the afternoons, and a poster exhibition will complement the scientific program.
The scientific program is further enriched by the direct contributions of the *Swiss Institute for Particle Physics* (CHIPP) and the *Swiss Neutron Science Society* (SGN). Together with the *Physikalische Gesellschaft Zürich* (PGZ) and the S*wiss Academy of Sciences* (SCNAT), we are co-organising a special Röntgen symposium (see p. 6). Thanks to all these collaborations, our annual meeting will offer again an exciting program, covering latest advancements of physics in a wide range of fields at its best.

Special thanks go to the Physics Department of UniFR, in particular to Dr. Baptiste Hildebrand and his team, for their generous help and support with the organisation.

Scientific Program

Plenary Session

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

- **Christof Fattinger,** F. Hoffmann-La Roche, Basel: *Molecular holograms for label-free biomolecular interaction analysis*
- **Rachel Grange,** ETH Zürich: *Beyond metals and semiconductors: nano-oxides for integrated photonic devices*
- **Lavinia Heisenberg,** ETH Zürich: *Gravitational Toolkit*
- **Sascha Quanz,** ETH Zürich: *Towards the direct detection of terrestrial exoplanets*
- **Daniela Rupp,** ETH Zürich: *Imaging ultrafast dynamics in clusters with intense X-ray pulses*
- **Christian Wüthrich,** Université de Genève: *Was there a time before time?*
- **Hugo Zbinden,** Université de Genève: *Quantum Cryptography*
- **NN**: *A Global View on Particle Physics (tbc)*

Furthermore, a public lecture is scheduled in the evening of Tuesday 30 June:

- **Kevin Heng,** Universität Bern: *Exoplanets and the Search for Extraterrestrial Life*

Special Focus

On 2 July a special session will focus on *A Global View on Particle Physics*.
Celebrating his 175th birthday and his discovery of the X-rays 125 years ago, a special *Wilhelm Conrad Röntgen symposium* will close the conference on 3 July.
More details on p. 6.

Topical Sessions

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

- Applied Physics and Plasma Physics
- Atomic Physics and Quantum Photonics
- Biophysics, Medical Physics and Soft Matter
- Condensed Matter Physics
- History and Philosophy of Physics
- Magnetism and Spintronics at the Nanoscale
- Nuclear, Particle- & Astrophysics *
- Quantum Beam Science: biophysics, materials physics and fundamental physics with neutrons, muons, electrons and X-rays **
- Start-ups: From great physics to innovative products

* in collaboration with CHIPP, ** in collaboation with SGN

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 1 July evening with an apéro and will continue on 2 July with a lunch buffet.
It is expected that **all** posters are presented on both session days.

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

The maximum poster size is A0 (portrait).

Award Ceremony

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

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

The award ceremony will be held on 1 July at 10:50h.

General Assembly

The general assembly is scheduled for 30 June in the morning. The agenda will be published in the next issue of the *SPG Mitteilungen*. We encourage all members to actively participate and contact the committee if special points of interest should be discussed at the assembly.

Conference Dinner

A conference dinner is scheduled for the evening of 2 July. Information on the location and more details will be available on our web site soon.

Vendors Exhibition

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

Abstract Submission: Deadline 7 March 2020

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

The submission of abstracts must be done online. Visit our webpage *www.sps.ch* and follow the link to the submission form. Further explanations are available there. The submission form will be activated shortly.
The conference program will be available in April 2020 on *www.sps.ch*. Please check the web regularly for further information and updates.

Conference Fees, Registration and Payment

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

Pay your conference fee in time and save money !

The regular fees, as shown in the table below, hold for payments reaching us before 1 June 2020.

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

(*) Students licence required

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

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

Registration Deadline: 1 June 2020

Special offer for non-members:

Do you plan to participate in our meeting and want to become a member of SPS ? Then take advandage of our special offer of CHF 190.- covering the conference fees and the membership for 2020. (CHF 210.- after 1 June) !
Just fill out the online-registration form, choose the option "Special offer", then download, print, fill and sign the admission form for new members, and return it as soon as possible to the SPS Secretariat.
The membership admission form is available on *www.sps.ch/fileadmin/doc/Formulare/anmeldeformular_d-f-e.pdf* .

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

Additional information for selected sessions

Theoretical Physics

Theoretical contributions are highly encouraged and will be included, as last year, 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)

Condensed Matter (KOND)

The condensed matter program welcomes contributions from all topics within Condensed Matter Physics, including magnetism, superconductivity, semiconductors and more.
For abstracts in the field of nanomagnetism and spintronics, please submit your abstract to the session below.

Contact: Henrik M. Rønnow (henrik.ronnow@epfl.ch), Laura J. Heyderman (laura.heyderman@psi.ch)

Magnetism and Spintronics at the Nanoscale

With this focus session we would like to highlight recent advances in the fabrication, measurement and control of novel functionalities in spintronic and nanomagnetic systems. We aim to bring together experimentalists and theoreticians from Switzerland, Austria, and the neighbouring countries exploring magnetic properties in thin films, interfaces, and nanostructures. Alberto Morpurgo (University of Geneva - Magnetic 2D materials), Cynthia Piamonteze (PSI - Magnetism in strongly correlated systems) and Olivier Boulle (Spintec/CEA, Grenoble, France - Spintronics) will give invited presentations at this session.

Contact: Ales Hrabec (ales.hrabec@psi.ch), Zhaochu Luo (zhaochu.luo@psi.ch), Laura J. Heyderman (laura.heyderman@psi.ch)

Quantum Beam Science: biophysics, materials physics and fundamental physics with neutrons, muons, electrons and X-rays.

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

Contact: Neutrons & muons: Henrik M. Rønnow (henrik.ronnow@epfl.ch), X-rays: Thorsten Schmitt (thorsten.schmitt@psi.ch), Electrons: Ivan Madan (ivan.madan@epfl.ch)

Start-ups: From great physics to innovative products

Has anyone ever approached you during your Master's or PhD thesis and asked if they "could also have one of those XYZ" that you have built? ("XYZ" = quantum sensor, laser, control electronics, you name it). Then you should definitely think about taking your work to the next level. In this year's session of the "Physics in Industry" section we will be looking with several invited speakers at what is needed to recognize and mature great ideas in a physics and engineering context and bring them to market. If you are in a physics-related start-up and have an exciting story to tell, please submit your abstract before the submission deadline.

Contact: Andreas Fuhrer (afu@zurich.ibm.com), Thilo Stöferle (tof@zurich.ibm.com)

A Global View on Particle Physics

The *European Particle Physics Strategy Update 2020* shall draw the next big vision and set priorities on how CERN shall evolve in the decades to come after the Large Hadron Collider program running out by the end of the next decade. A report by the European Strategy Group (ESG) will become publicly available in May 2020, which will not go unnoticed by press and public.

The aim of this event is to give a broad overview on particle physics most important questions and to highlight the process of the work done by the ESG. Over the last two years, the whole particle physics community was consulted by the ESG and to which CHIPP contributed a coherent Swiss view. The options brought forward include large-scale linear and circular lepton and hadron colliders, all with their complementary potentials, reaches, timelines and cost. These are complemented with a rich non-collider based experimental program, and include technology R&D and theoretical studies. A global perspective taking into account experimental existing and pledged facilities in Asia, the United States and elsewhere is needed to derive a strategy that will be supported and that can be realised.

Wilhelm Conrad Röntgen Symposium

On the last day of the SPS annual meeting on 3 July, a public symposium is dedicated to the physicist *Wilhelm Conrad Röntgen* (1845-1923), whose 175th birthday is being remembered worldwide this year and who discovered the radiation named after him 125 years ago.

Three talks will highlight Röntgen's biography, which led to the discovery of X-rays and the first Nobel Prize in Physics, as well as the current state of research and applications, in which X-rays play a fundamental role today.

The program starts after the general coffee break as follows:

- 11:15 - 12:00, **Ralph Claessen**, University of Würzburg
  Röntgen's discovery: from serendipity to scientific revolution
- 12:00 - 12:45, **Marco Stampanoni**, ETH Zürich
  125 years of X-ray imaging and still eager to push further
- 12:45 - 13:30, **Clemens Schulze-Briese**, Dectris Ltd. Baden
  X-rays in industry and society, what we do today and what can be done tomorrow

The public is cordially invited to attend these lectures that will be given in English; admission is free and registration is not required.

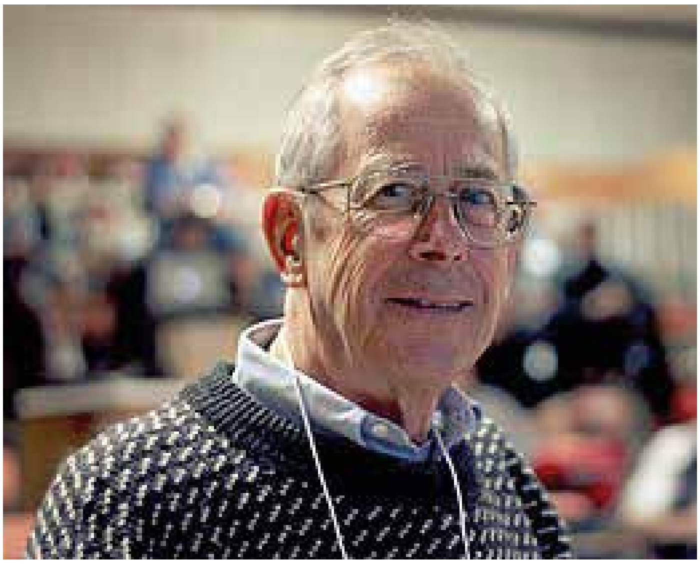
The Wilhelm Conrad Röntgen Symposium is jointly organized by the Swiss Physical Society SPS, the Physikalische Gesellschaft Zürich PGZ, and the Swiss Academy of Sciences SCNAT.

Philip James Edwin Peebles
Laureate of the Physics Nobel Prize 2019

Ruth Durrer, Université de Genève

It is a honour for me to write a short commentary on the Nobel Prize allocation to Philip James Edwin Peebles, or Jim, as everybody calls him. I had the great chance to spend two years as a post-doc in Princeton, where Jim was leading the 'gravity-group' at the time. From him I learned that groups work best with a flat hierarchy where everybody can communicate her/his ideas, ask questions and participate in discussions in a relaxed and constructive atmosphere. This was the spirit of Jim's 'lunch seminars' with the famous 'hoagies' from the Hoagie Haven at Nassau street.

Jim Peebles was awarded the Nobel prize 2019 "*for theoretical discoveries in physical cosmology*". The Press release says: "*James Peebles' insights into physical cosmology have enriched the entire field of research and laid a foundation for the transformation of cosmology over the last fifty years, from speculation to science. His theoretical framework, developed since the mid-1960s, is the basis of our contemporary ideas about the universe.*"



This statement could not be more true. In the beginning of the 1960ties, it was still debated whether the 'steady state model' or the 'Big Bang model' was a better description of the physical Universe. The discovery of the Cosmic Microwave Background (CMB) put an end to this debate. This relic radiation from the Big Bang was natural only in an adiabatically expanding and cooling Universe, as it had been predicted already in the 1940ties by George Gamow and collaborators. James was co-author of the theoretical interpretation paper published in 1965 [1], back-to-back with the Nobel Prize (1978) winning CMB discovery paper by Penzias and Wilson [2].

The discovery of the CMB led to a paradigm change and convinced most workers in the field that Big Bang Cosmology was basically correct, nevertheless the details (like the matter and radiation content of the Universe or the value of its spatial curvature) were still completely unknown.

The Big Bang model of cosmology is based on Einstein's General Relativity with the assumption that on large enough scales, the distribution of matter and radiation in the Universe is homogeneous and isotropic with only small initial fluctuations. This assumption leads to an expanding and cooling Universe [1]. In the past, the Universe was very hot and its energy density was dominated by radiation. Subsequently it expanded and cooled down adiabatically. At a temperature of about $kT \sim 0.1$ MeV the first atoms, mainly Helium, but also Deuterium and traces of Lithium formed, a phase called 'primordial nucleosynthesis'. At $kT \sim 0.25$ eV the remaining protons and electrons recombined to neutral hydrogen and the Universe became transparent to the cosmic radiation which propagated freely, affected only by cosmic expansion redshifting the thermal radiation to the present CMB temperature of about 2.73 K. A picture of the CMB radiation is literally a 'photograph' of the Universe when it was about 380'000 years old.

Somewhat earlier, dark matter started dominating the energy density of the Universe and small initial fluctuations could start to collapse under their own gravity into the structures (galaxies, clusters, filaments and voids) which today make up the 'cosmic web'. In the absence of dark matter, radiation pressure would have prevented the growth of fluctuations until well after recombination and the time would have been too short to form the presently observed structures.

An interesting idea to generate initial fluctuations was proposed in the 1980ties via an 'inflationary phase', i.e., a phase of very rapid expansion which may have preceded the thermal state of the hot Big Bang. Quantum fluctuations of the scalar field dominating such a stage of inflation are stretched into large scale coherent classical fluctuations with a nearly scale invariant spectrum. Such fluctuations have been observed in the CMB (Nobel Prize 2006) and, in the presence of dominant, sufficiently cold, dark matter, they can evolve into the observed cosmological large scale structure (LSS).

Finally, at the end of the 20th century and beginning of the present century, it was becoming clear that the expansion of the Universe is presently accelerating (Nobel Prize 2011), not decelerating as one would expect from universal gravitational attraction. Such an accelerated expansion can be obtained by adding a cosmological constant, Λ, to Einstein's field equations (as actually Einstein himself did to obtain his static Universe in 1917). There are also other possibilities for a gravitationally repulsive component, today generically termed 'Dark Energy'.

All these ingredients have led to the standard model of cosmology, the so called ΛCDM model, with an energy density which is presently dominated by the cosmological constant, contributing about 68% followed by 27% of dark matter and

1 A contracting Universe would also be possible but it does not agree with observations.

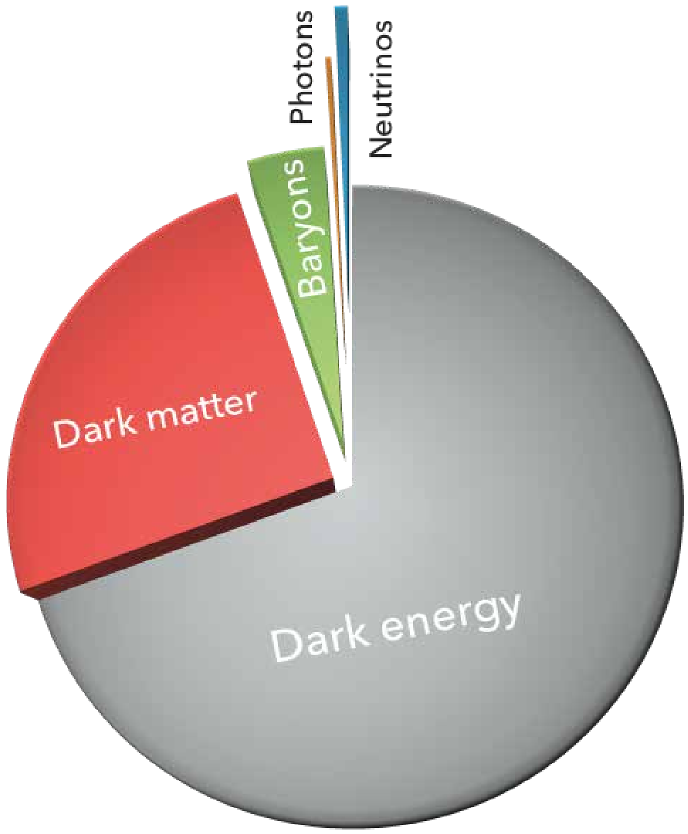


Figure 1: Composition of the Universe today. Ordinary matter makes up only 5% of the energy density of the Universe. Dark Matter, an unknown form of matter that does not emit light, contributes about 27% while Dark Energy, an even more mysterious component associated with the accelerated expansion of the universe, makes up 68% (Neutrinos and photons even though much more numerous contribute far less than 1% to the present energy density of the Universe.).

only about 5% of ordinary matter, baryons. The CMB radiation contributes at present only a fraction of about 5.4 × 10^{-5} to the energy budget of the Universe, much less than the neutrinos which contribute (1.4 to 5) × 10^{-3}, depending on the sum of the neutrino masses [2], see Fig. 1. This is the minimal cosmological model with only 5 fundamental parameters (the present dark matter and baryon densities, the cosmological constant, as well as the amplitude and the slope of the primordial spectrum of scalar fluctuations) and 1 fudge factor (the optical depth to the CMB or the redshift of re-ionisation). It fits most present cosmological data and its 6 parameters are determined with a precision of about 1% or better. As an example, the fit to the about 2500 CMB temperature fluctuation data points from the Planck satellite is shown in Fig. 2.

There are a few tensions with some data, most notably the different methods to measure the value of the Hubble constant, H_0. These may or may not hint towards shortcomings of the ΛCDM model, which certainly from the theoretical side is far from satisfying. But then, a model which agrees with all data must be wrong, because some data are wrong.

James Peebles contributed in many very important ways to establishing the present cosmological standard model. I think it is fair to say that he is the world's leading theoretical cosmologist.

He has pioneered our understanding of primordial nucleosynthesis and has calculated the abundance of the light elements [4]. Together with Robert Dicke he has predicted the existence of the Cosmic Microwave Background and together with David Wilkinson and Peter Roll they actually searched for this radiation while Penzias and Wilson discovered it accidentally. He studied the formation of cosmological large scale structure by gravitational instability and predicted the existence of cold dark matter (CDM), needed to explain the clumpy structure of matter together with the smoothness of the CMB [5, 6]. Already in the 1980ties and 90ties he advocated that the matter density of the Universe was not sufficient for a flat so called 'Einstein de Sitter' solution and that either negative curvature or a cosmological constant was needed to explain the data, see e.g. [7]. He developed not only the basic ideas but also analytical and numerical tools to

- calculate primordial nucleosynthesis
- study anisotropies in the CMB
- investigate the formation of large scale structure
- describe the statistical properties of the galaxy distribution.

In all these major fields of cosmology, James Peebles played a leading role.

He invented the 'cold dark matter' (CDM) model. Together with B. Ratra he wrote one of the first papers on quintes-

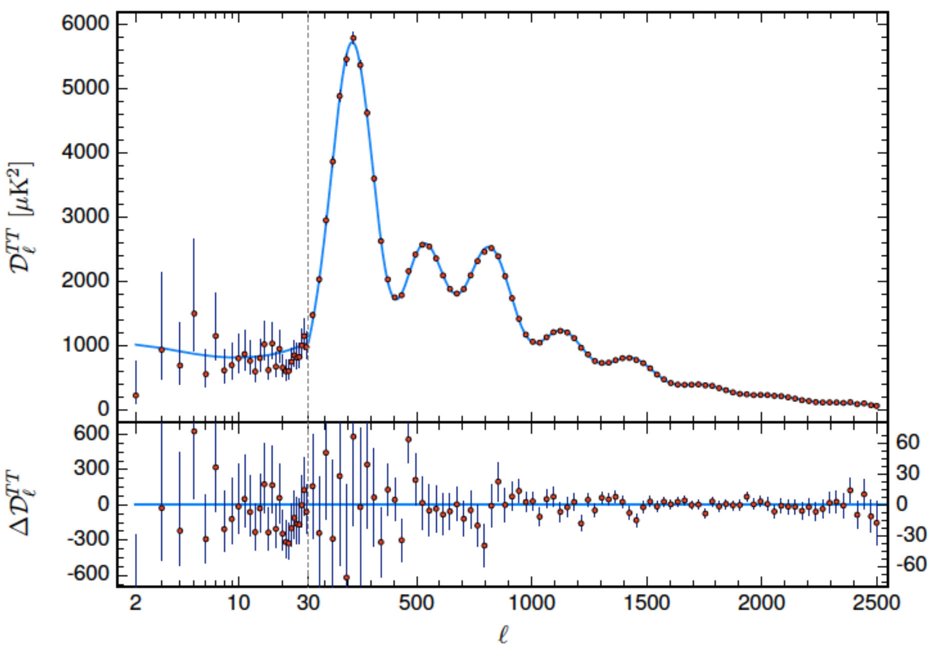


Figure 2: The temperature fluctuation spectrum $\ell(\ell+1)C_\ell/(2\pi)$ as measured by the Planck satellite (the red points with error bars represent binned data points) and the 6 parameter basic model (blue line). Figure from [3].

2 For 1.4 × 10^{-3} I assume the minimal allowed value from neutrino oscillations of 0.06 eV while for 5 × 10^{-3} I assume a Planck limit of about $\sum_i m_{\nu_i} < 0.23$ eV.

sence or dark energy at a time when nobody was working on this subject [8].

However, during all this time, when he was leading what later became the main stream models in cosmology, he always also studied alternatives like his baryon isocurvature model [9] or models of large scale structure with negative spatial curvature [10] and more. He always kept an open mind, remained critical and identified loopholes in arguments which tried to 'cement' the standard wisdom at any time.

A few words to Jim's career:
James Peebles was born in Saint-Boniface near Winnipeg in Canada and did his undergraduate studies in Manitoba. In 1958 he move to Princeton where he started a PhD under the supervision of Robert Dicke. In an interview with the CERN EP Newsletter in 2016 he said about this time:

> *"I felt very uncomfortable about the modest experimental evidence in support of any cosmology theories. I did not think I would spend much time in this field, but, surprisingly, I kept finding things to explore during my entire career."*

He spend most of his professional life in Princeton, since 1984 as Albert Einstein Professor of Science.

Peebles received many awards and distinctions like, e.g., the Eddington Medal (1981), the Dannie Heineman Prize (1982) the Georges Lemaître Prize (1995), the Peter Gruber Prize in cosmology (with A. Sandage, 2000) and the Tomalla Prize (2003). I was happy to be able to hand over to him this last distinction.

Peebles' Nobel Prize marks the fourth one during this century for the field of cosmology and gravity after the 2006 Prize for the COBE experiment (Mather & Smoot), the 2011 Prize for the discovery of accelerated expansion with Supernova measurements (Perlmutter, Schmidt & Riess) and the 2017 Prize for the LIGO experiment (Weiss, Barish & Thorne). These past prizes were mainly for experimental work, this year's prize goes to a theoretical cosmologist.

Peebles is certainly an excellent choice in a time when cosmology will enter a new area by mapping out the distribution of galaxies in the entire visible Universe. To interpret these data, the statistical tools pioneered by James Peebles will remain of utmost importance.

References

[1] R. H. Dicke, P. J. E. Peebles, P. G. Roll and D. T. Wilkinson, Cosmic Black-Body Radiation, Astrophys. J. **142** (1965) 414. doi:10.1086/148306
[2] A. A. Penzias and R. W. Wilson, A Measurement of excess antenna temperature at 4080-Mc/s, Astrophys. J. **142** (1965) 419. doi:10.1086/148307
[3] N. Aghanim et al. [Planck Collaboration], Planck 2018 results. VI. Cosmological parameters, arXiv:1807.06209 [astro-ph.CO].
[4] P. J. E. Peebles, Primeval Helium Abundance and the Primeval Fireball, Phys. Rev. Lett. **16** (1966) 410. doi:10.1103/physrevlett.16.410
[5] P. J. E. Peebles, Formation of Galaxies in Classical Cosmology. Nature, **220**, (1968) 237.
[6] P. J. E. Peebles, The Large Scale Structure of the Universe. Princeton University Press (1980).
[7] M. Davis and P. J. E. Peebles, A survey of galaxy redshifts. V. the two-point position and velocity correlations, Astrophys. J. **267** (1983) 465. doi:10.1086/161714
[8] B. Ratra and P. J. E. Peebles, Cosmological Consequences of a Rolling Homogeneous Scalar Field, Phys. Rev. D **37** (1988) 3406. doi:10.1103/PhysRevD.37.3406
[9] P. J. E. Peebles, An isocurvature model for early galaxy assembly, Astrophys. J. **483** (1997) L1. doi:10.1086/310738
[10] B. Ratra and P. J. E. Peebles, CDM cosmogony in an open universe, Astrophys. J. **432** (1994) L5. doi:10.1086/187498

Michel Mayor and Didier Queloz: 2019 Physics Nobel Prize Laureates

Willy Benz, Physikalisches Institut, Universität Bern

This year's Laureates have transformed our ideas about the cosmos. While James Peebles' theoretical discoveries contributed to our understanding of how the universe evolved after the Big Bang, Michel Mayor and Didier Queloz explored our cosmic neighbourhoods on the hunt for unknown planets. Their discoveries have forever changed our conceptions of the world. With these strong words, the Nobel Prize committee has recognized their unique contributions to science and knowledge.

Changing our conceptions of the world, nothing less. The dream of all scientists. Not just leaving footprints along a well-travelled path but opening a new trail from which new perspectives can emerge. They have done it and have been recognized for it. Congratulations.

For someone working in planetary sciences, the discovery by Michel Mayor and Didier Queloz in 1995 was nothing else than a revolution. To measure its impact, it is necessary to remember that at the time only the planets in our solar system were known. Its characteristic architecture, small rocky planets close to the sun and giant gaseous planets further away, was considered as an unquestionable generic feature of all planetary systems. The discovery by the two Nobel Laureates shatters it all! A giant planet (roughly half the mass of Jupiter) orbiting its star (51 Pegasi) at a distance seven times smaller than Mercury is to our sun. Game over! We knew immediately that something was wrong, no room for arguing. The discovery of a single object was enough to send us all back to the drawing board!

A obvious question comes to mind: Why did it take so long for detecting the first planet orbiting another star like the sun? The answer is easy: contrast and separation. Compared to the star they orbit, planets are extremely faint. Typically, the contrast ratio is of order 10^8 - 10^{10} in the visible and 10^6 in the infrared. If we couple this huge contrast ratio with the fact that as seen from us, the separation between planet and star is very small (typically a fraction of an arc-second or even much less), it becomes obvious that "seeing" planets is an enormous challenge even for our most modern telescopes and instruments. In fact, it is such a challenge that clever indirect methods have been used to detect plan-

Michel Mayor and Didier Queloz during the Nobel-banquet in Stockholm on 10 December 2019.

ets while waiting for high-contrast high-resolution imaging to mature. While planets cannot be seen, the host star is clearly visible. With precise Doppler measurements, their small motions resulting from the gravitational pull of planet(s) in orbit (a dynamical effect) can be measured and a minimum mass for the planet determined. With ultra-precise measurements of the intensity of the light received from the star, the slight dimming resulting from a planet transiting in front of the star (a photometric effect) can be detected and the size of the planet determined. For planets measured with both techniques, mass and radius are known and therefore their mean density can be computed, a first step in the characterisation of exoplanets.

Michel Mayor was an astronomer initially interested in the kinematics of stars. The need for high precision data for developing dynamical models of galaxies and stellar clusters pushed him to consider the possibility of developing a more accurate method. In the seventies, he turned his attention towards a cross-correlation technique pioneered by Roger Griffin in the UK and imported it to Geneva Observatory. By the time, I started my PhD thesis under his supervision in 1979, his first spectrograph, named Coravel, could measure velocities of stars to a precision of the order of one km/s in just minutes. A first revolution in stellar dynamics but not quite enough for Michel Mayor and his drive for precision. A path towards an even better machine was beginning to take shape. With his graduate student Didier Queloz, who wrote a large part of the software driving the machine and carried out many observations at the telescope, and a group of dedicated engineers and technicians, the spectrograph ELODIE was built and installed on the 1.93 m telescope at the Observatoire de Haute-Provence in the South of France. This new generation machine was now capable of measuring velocities to a precision of order 10 m/s, a factor 100 improvement over the previous instrument. Achieving this precision is what made the detection of the first exoplanet possible in 1995.

As mentioned above, this single discovery had an enormous impact on the field and triggered an unprecedented explosion of activities. Groups in the US using a different technique (iodine cell) quickly became serious competitors but the Geneva group managed to develop their cross-correlation technique further by, among other, enclosing the spectrograph in a dedicated pressure- and temperature-stabilized vessel. A collaboration between the University of Geneva, the University of Bern, the Service d'Aéronomie and the Observatoire de Haute-Provence was established to build under the leadership of Michel Mayor the HARPS spectrograph for the European Southern Observatory (ESO) 3.6 m telescope in La Silla, Chile. Commissioned early 2000 and reaching a precision of better than 1 m/s, HARPS remained for over fifteen years the most powerful exoplanet finding machine based on radial velocity measurements. It definitively established Michel Mayor's cross-correlation approach as the method of choice for precise radial velocity measurements. Earlier this year, the latest generation of spectrographs based on this technique was installed at the incoherent Cassegrain focus of the four 8.5 m ESO telescopes at Paranal Observatory in Chile. Built by a Consortium led by the University of Geneva and a new generation of instrument builders having been inoculated by Michel Mayor with the high-precision virus, the instrument now reaches 10 cm/s precision and can combine the light of all four telescopes, which corresponds to an effective light collecting area equivalent to a 16 m telescope. The world's most stable spectrograph allowing measurements ten thousand times more precise than the original built forty years earlier. Forty years of painstakingly and consistently improving a measurement technique!

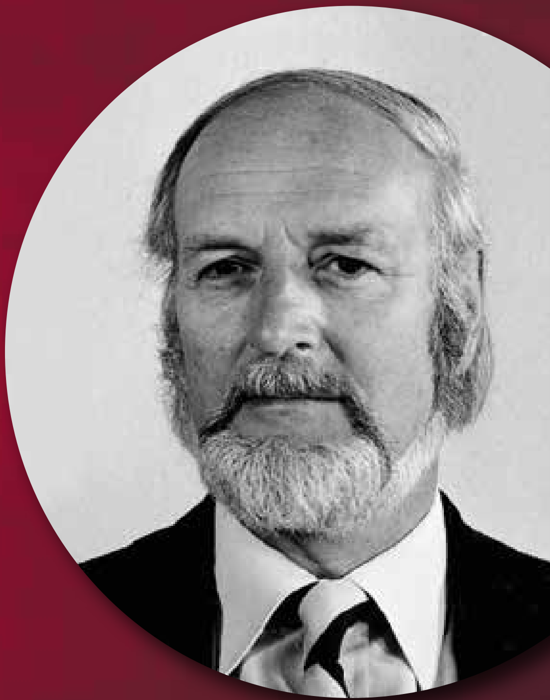
No, the discovery of Michel Mayor and Didier Queloz in 1995 was not due to chance, but to a clear vision of what technology was needed and to an incredible drive to get it done at a time when nearly everyone else thought it impossible. Despite this, the Swiss system (at both university and federal level) allowed Michel Mayor and Didier Queloz to obtain the support they needed to pursue their research. This constitutes a textbook example of the necessity to sustain curiosity driven research over significant periods of time especially in experimental areas where novel technology/ instruments must be developed before new frontiers can be reached.

Today, nearly 25 years later and over 4000 additional discoveries, it is the diversity of planets and planetary systems that has become the rule. We now know that planets are extremely common objects in the Universe, that they come in all sizes with the smaller ones being more numerous. Some are Earth-like and are located at distance to their star such that they are temperate opening the possibility to eventually search for life as we know it on Earth. To allow for this, the next generation infrastructures, technology, and measurement techniques are developed all over the world and will become available within the next decade or so.

The discovery of the first exoplanet by Michel Mayor and Didier Queloz has not only changed our conception of the world, it also triggered an explosion of activities world-wide and opened the door to the search for life outside the solar system. A momentous achievement well deserving of the highest honour, the Nobel Prize.

Symposium
Zur Erinnerung an Jean-Pierre Blaser

SIN und PSI Gründungsdirektor



Sa, 29. Februar 2020
09.00 – 15.15 Uhr

ETH Hauptgebäude, Rämistrasse 101
Auditorium Maximum HG F 30

Programm

09.00 Uhr	**Kaffee**
09.30 Uhr	**Begrüssung und Vorwort** (R. Eichler)
09.45 Uhr	**Das Wunder von Villigen** (W. Joho)
10.15 Uhr	**Der Beitrag der Schweizer Mesonenfabrik zur Forschung in der Teilchenphysik** (P. Truöl)
10.45 Uhr	**Vorgeschichte und Beginn der µSR Spektroskopie am SIN – ein persönlicher Rückblick** (A. Schenck)
11.15 Uhr	**Hochstromausbau und SINQ** (E. Steiner)
11.45 Uhr	**Stehlunch**
13.00 Uhr	**Teilchentherapie am SIN/PSI – Beschleunigertechnologie im Dienst der Medizin** (E. Pedroni)
13.25 Uhr	**Strahlentherapie mit geladenen Teilchen – medizinische Pionierleistung am SIN/PSI** (G. Goitein)
13.50 Uhr	**Astrophysik am SIN/PSI** (A. Zehnder)
14.20 Uhr	**SIN und EIR – die Zukunft muss gestaltet werden** (A. Pritzker)
14.50 Uhr	**Das Legat** (H.R. Ott)
15.15 Uhr	**Ende der Veranstaltung**

Anmeldung bis: 24. Februar 2020
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Progress in Physics (71)

New magnetic two-dimensional semiconducting layered materials for spintronic applications

Zurab Guguchia and Alex Amato, Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institute

Introduction

Spintronics, or spin-based electronics, is one of the promising next generation information technology. It makes use of the quantum property of electrons, such as spin [1, 2], as information carriers and possesses potential advantages like speeding up the data processing, high circuit integration density, and low energy consumption. Magnetic semiconductors, combining the properties and advantages of both magnets and semiconductors, form the basis for spintronics. All semiconductor spintronic devices act according to the following simple scheme: information is stored (written) into spins as a particular spin orientation; the spins, being attached to mobile electrons, carry the information along a wire; and the information is read and processed at a terminal. But spintronics applications require novel magnetic semiconducting materials, which can be produced as very stable thin layers and incorporated in the devices.

Along these lines, transition metal dichalcogenides (TMDs), a family of two dimensional (2D) layered materials like graphene, have appeared as the most promising platforms due to their exciting mechanical, electronic and optoelectronic properties [3 – 9]. TMDs share the same formula, MX_2, where M is a transition metal and X is a chalcogen. They have a layered structure and crystallize in several polytypes, including 2*H*-, 1*T*-, 1*T'*- and T_d-type lattices. Much interest is focused on the cases where the transition metal M is either Molybdenum (Mo) or Tungsten (W). Hence, the 2*H* forms of these compounds are semiconducting and can be mechanically exfoliated to a monolayer. The unique properties of the TMDs, especially in the monolayer form, have triggered a wealth of device applications such as: magnetoresistance and spintronics, high on/off ratio transistors, optoelectronics, valley-optoelectronics, superconductors and hydrogen storage. Many of these interesting properties arise due to the strong spin-orbit interaction present in these materials arising from the presence of the heavy metal ion. While there are many studies focused on the spin-orbit coupling and the interesting consequences for electrical and optical properties in these materials, there are very limited, and mostly theoretical, studies on the intrinsic magnetism [10 – 12]. Theoretical and experimental work shows that, in the absence of crystalline imperfections, the Mo-based TMDs are nonmagnetic.

Combining a wealth of different technique, in particular the muon-spin rotation/relaxation technique, we discovered [9] novel magnetism in these very stable semiconducting materials: molybdenum diteluride ($MoTe_2$) and molybdenum diselenide ($MoSe_2$). In the same materials, we detect the presence of intrinsic dilute self-organized magnetic tellurium/selenium antisite defects (irregularities in the arrangement of atoms) using scanning tunneling microscopy measurements, a finding that is well supported by calculations based on Coulomb corrected density functional theory, a method that models and studies the structure of complex systems with many electrons.

Methods

We studied, both polycrystalline and single-crystalline, samples of 2*H*-$MoTe_2$ and 2*H*-$MoSe_2$ by means of powerful experimental techniques such as muon spin relaxation/rotation (μSR) [13], scanning tunneling microscopy (STM) and X-ray pair distribution function (PDF) experiments. Hubbard-corrected density functional theory calculations (DFT + U) were also used to gain insights into the experimental results. μSR

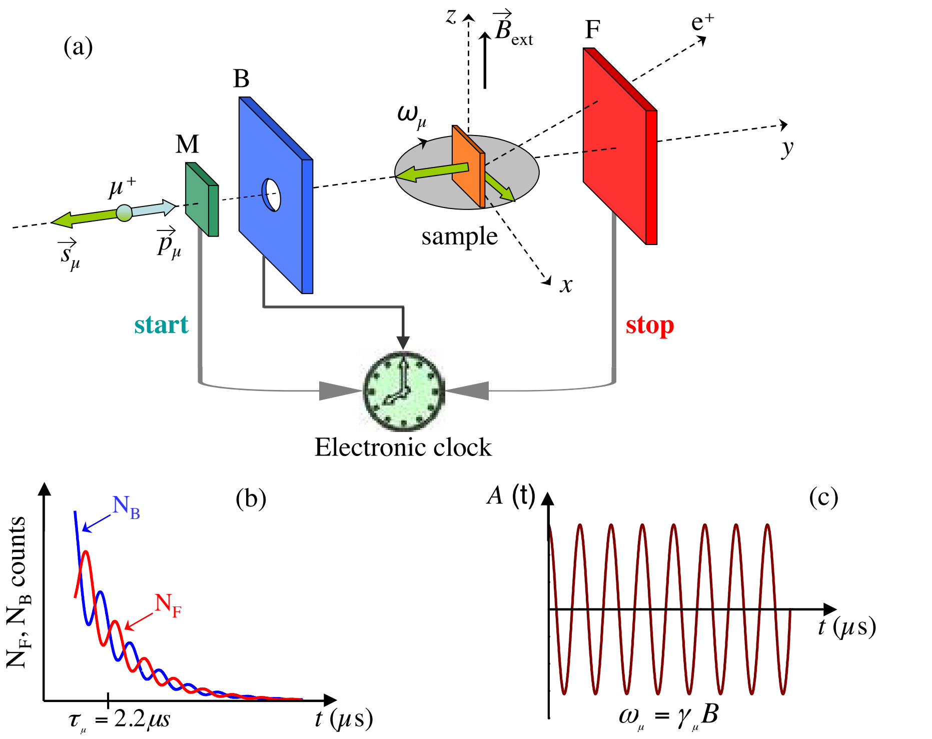

Fig. 1: Principle of a μSR experiment. (a) Overview of the experimental setup. Spin polarized muons with spin $\mathbf{S}_\mu$ antiparallel to the momentum $\mathbf{p}_\mu$ are implanted in the sample placed between the forward (F) and the backward (B) positron detectors. A clock is started at the time the muon goes through the muon detector (M) and is stopped as soon as the decay positron is detected in the detectors F or B. (b) The number of detected positrons N_F and N_B as a function of time for the forward and backward detector, respectively. (c) The so-called asymmetry (or μSR) signal is obtained by essentially building the difference between N_F and N_B.

experiments serve as an extremely sensitive local probe technique to detect small internal magnetic fields and ordered magnetic volume fractions in magnetic materials. We also used a unique high-pressure μSR instrument to study the magnetic properties under hydrostatic pressure [14, 15]. STM has the ability to measure atomic and electronic structure with atomic resolution, and has been used extensively in the past to study local electronic properties in TMDs and other 2D materials [16]. The techniques of STM and μSR complement each other ideally, as we are able to study the magnetic properties of these crystals sensitively with μSR experiments and correlate these magnetic properties with atomic and electronic structure measured by STM. The results are published in a journal of the American Association for the Advancement of Science [see Ref. 9].

Muon Spin Rotation Technique

In a μSR experiment, spin-polarized muons μ^+ are implanted into the sample one at a time [13] (see Fig. 1). Muons thermalize very quickly at interstitial lattice sites, where they act as magnetic microprobes. As the muon undergoes a parity-violating decay, the time evolution of the muon spin polarization *P(t)* of the muon ensemble can be reconstructed by recording the anisotropic emission of the positrons (muon-decay product) which are preferentially emitted along the direction of the muon spin at a moment of the decay.

In a magnetic material, the muon spin precesses in the local field $\mu_0 H_{int}$ at the muon site with a Larmor frequency directly related to the internal field. Moreover, the μSR technique has a unique time window (10^{-4} s to 10^{-11} s) for the study of magnetic fluctuations in materials, which is complementary to other experimental techniques such as neutron scattering, NMR or magnetic susceptibility. High sensitivity (because of the large magnetic moment of the muon) to extremely small static magnetic moments (down to 10^{-3} - 10^{-4} μB) and the broad time window makes μSR a powerful tool to investigate magnetism in solid state physics. μSR is also valuable for studying materials in which magnetic order is random or of short range [17].

Results

Zero-field (ZF) μSR time spectra for single-crystalline sample of $MoTe_2$, recorded for various temperatures in the range between 4 and 300 K, are shown in Fig. 2b. At the highest temperature T = 300 K, μSR reveals that nearly the whole sample is in the paramagnetic state. The paramagnetic state causes only a very weak depolarization of the μSR

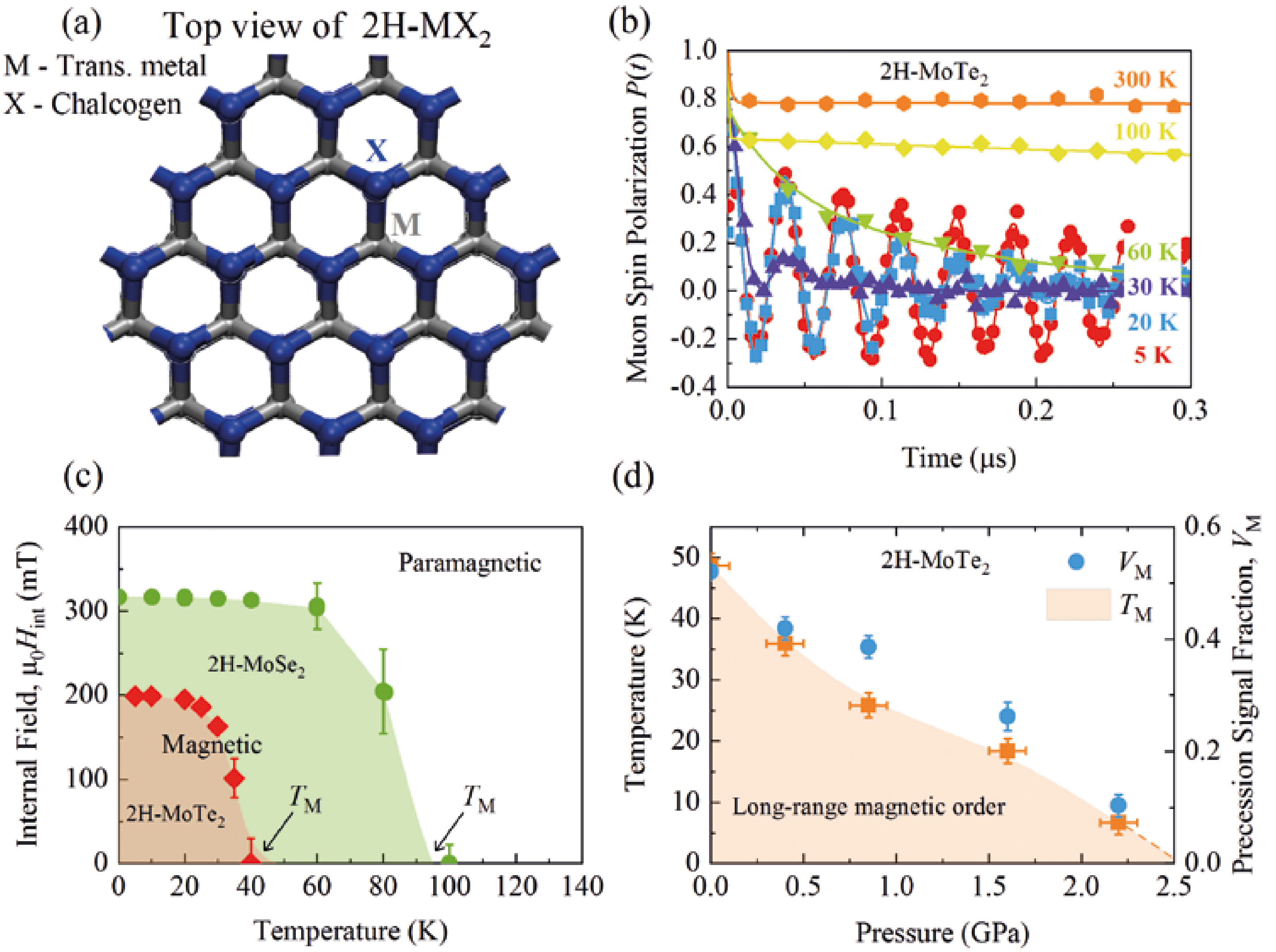

Fig. 2: (a) Hexagonal crystal structure of transition metal dichalcogenide. (b) ZF μSR time spectra for the single-crystal of 2H-$MoTe_2$ recorded at various temperatures up to 300 K. (c) Temperature dependence of the internal field $\mu_0 H_{int}$ of 2H-$MoTe_2$ and 2H-$MoSe_2$ as a function of temperature. (d) Magnetic transition temperature T_M and magnetic volume fraction V_M as a function of pressure [adapted from Ref. 9].

signal. This weak depolarization and its Gaussian functional form originate from the interaction of the muon spin with randomly oriented nuclear magnetic moments. Upon cooling, first, a fast decaying μSR signal is observed. Below $T_M \simeq 40$ K, in addition to the strongly damped signal, a spontaneous muon spin precession with a well-defined frequency (corresponding to an internal field $\mu_0 H_{int}$ at the muon site) is observed, which is visible in the raw data (Fig. 2b). Figure 2c shows the temperature dependence of the local magnetic field $\mu_0 H_{int}$ for $MoTe_2$. There is a smooth increase of $\mu_0 H_{int}$ below $T_M \simeq 40$ K, reaching the saturated value of $\mu_0 H_{int} = 200$ mT at low temperatures. The observation of a spontaneous muon spin precession is a clear signature of the occurrence of a static and long-range magnetic state in the semiconducting 2*H*-$MoTe_2$ system below $T_M \simeq 40$ K, and constitutes a remarkable finding. The long-range magnetic order was also observed in the related system 2*H*-$MoSe_2$ (see Fig. 2c), but with higher ordering temperature $T_M \simeq 100$ K and with higher local magnetic field $\mu_0 H_{int} \simeq 300$ mT. This difference might be related to the different magnetic structures in 2*H*-$MoSe_2$ than in 2*H*-$MoTe_2$. In addition to oscillations, which arises from the precession of the spin of the diamagnetic muon around the internal magnetic field, we observe another component, which exhibits a strong relaxation. In addition, it is evident from the ZF μSR data that upon cooling, the oscillating component develops at the cost of the strongly damped fraction and both fractions together cover the whole volume of the sample. The strongly damped signal observed in these compounds is attributed to the presence of a muonium fraction. Muonium, a bound state formed by a positive muon and an electron, may form in semiconductors [17]. In the bound state, the muon is much more sensitive to magnetic fields than as a free probe, because its magnetic moment couples to the much larger electron magnetic moment, thus amplifying the oscillations and the depolarization effects. Therefore, even small variations of the internal magnetic field may cause a strong depolarization such as that observed in the spectra at early times. In any case, the presence of the oscillating signal in the ZF μSR time spectra in these compounds is a clear signature of magnetism in the nearly full volume of the sample. Moreover, we determined that hydrostatic pressure has a significant effect on the magnetic properties of these materials. Namely, we see both a suppression of the magnetically ordered fraction and a decrease of the magnetic order temperature T_M as a function of pressure (Fig. 2d). This strong pressure dependence of magnetism is very encouraging, because it indicates that one can have control over the magnetic properties. This also means that uniaxial strain, which is another interesting and widely applied tuning parameter, might also be useful in these materials.

Previous theoretical work [11] and simple chemical bonding considerations indicate that the Mo atoms in 2*H*-$MoTe_2$ are in a nonmagnetic 4d^2 configuration. We therefore investigated the presence of defects using the high-resolution STM in the crystals measured by μSR. This STM study indicates the presence of intrinsic dilute defects (see Fig. 3a). Note that two major defects, i.e. chalcogen-antisites (Fig. 3b) (where a molybdenum atom substitutes the Tellurium/Selenium atom) and metal-vacancies (Fig. 3c), were found in these materials synthesized by two different methods - chemical vapor transport and self-flux growth [9]. Commercial samples were also tested and the same types of defects were detected, indicating that defects are truely intrinsic for $MoTe_2$ and $MoSe_2$ and that they are randomly distributed in the crystal lattice. Scanning tunneling spectroscopy spectra, taken on the chalcogen-antisites defects (Mo_{sub}) always display a deep in-gap state, while the metal vacancy (Mo_{vac}) does not show such a feature [9].

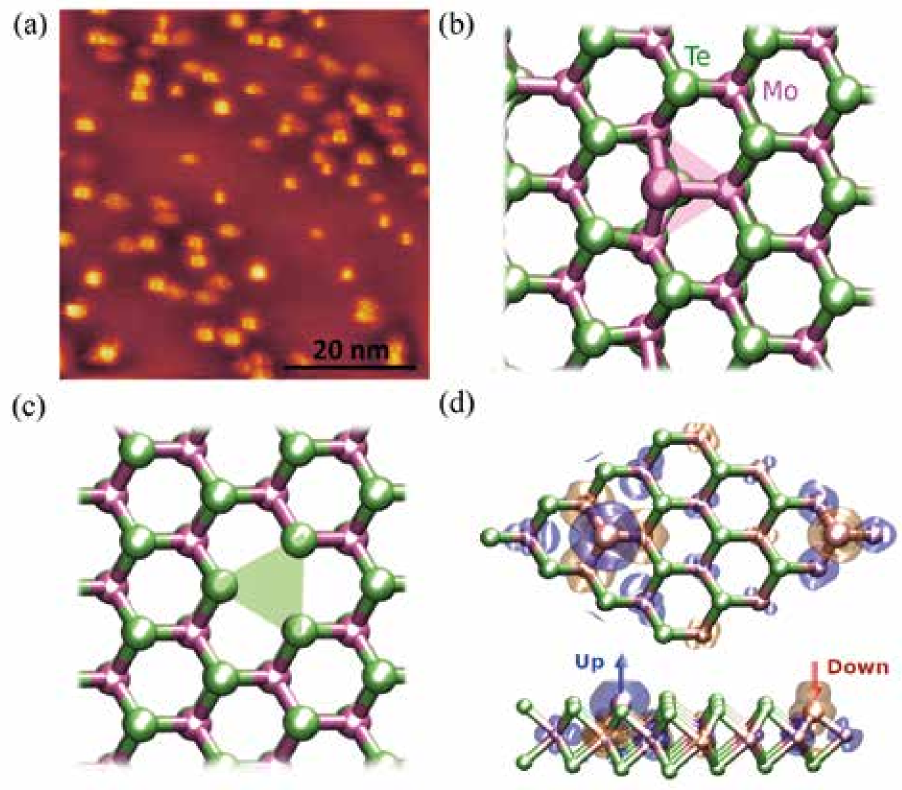

Fig. 3: (a) Large-scale atomic-resolution STM topography (note the 20 nm scale) of the 2H-$MoTe_2$ surface. The image reveals an approximately uniform density of two types of defects over the entire surface. (b) DFT+U–optimized geometry for the chalcogen-antisite Mo_{sub} defect. (c) DFT+U–optimized geometry of the metal-vacancy defect Mo_{vac}. (d) Magnetization density on the top surface of bulk 2H-$MoTe_2$ in the antiferromagnetic configuration. Spin-up and spin-down states are shown in faint blue and orange isosurfaces, respectively. Note that spins also couple antiferromagnetically at the local level between the chalcogen-antisite defect and the nearest Mo atoms [adapted from Ref. 9].

Having identified the primary defect types in our crystals, we performed Hubbard corrected DFT+U calculations to examine their magnetic properties [18]. DFT indicates that the chalcogen-antisite defects Mo_{sub} are magnetic, while metal-vacancy defects Mo_{vac} do not introduce a significant local moment [9]. The spin-polarized density of states shows that the localized Mo-4*d* states at the Fermi level carry most of the magnetization with minor contribution from *p* states of the Te atoms. DFT also determines that the chalcogen-antisite Mo_{sub} defects are coupled antiferromagnetically to the nearest-neighbor Mo atoms, as shown in Fig. 3d. The magnetic moments at the nearest-neighbor Mo atoms can reach 0.10

to 0.40 μ_B/atom, with smaller contributions for second and third neighbors (0.02 to 0.08 μ_B/atom). The Tellurium atoms show negligible spin polarization. Similar effects have previously been observed [18] in graphene with different adsorbates and substitutional metal atoms.

Discussion

Our muon measurements unambiguously establish 2*H*-$MoTe_2$ and 2*H*-$MoSe_2$ as intrinsic magnetic, moderate bandgap semiconductors [9]. The μSR results indicate magnetic order below $T_M \simeq 40$ and 100 K for $MoTe_2$ and $MoSe_2$, respectively. In the same materials, STM measurements demonstrate the presence of intrinsic dilute self-organized magnetic Tellurium/Selenium-antisite defects, a finding that is supported by Coulomb corrected DFT. The defects have a large electronic impact. Although the exact link between μSR and STM/DFT results is not yet clear, both results together constitute a first strong evidence concerning the relevance of magnetism in the TMDs physics. At present, one does not understand all the mechanisms at play for the origin of magnetism in these materials. Low-density of the chalcogen-antisite defects cannot give rise to long-range magnetic order, unless these defects have electronic coupling to the semiconductor valence electrons. The presence of such spin-polarized itinerant electrons would imply that these materials are dilute magnetic semiconductors. Recently, ferromagnetism in VSe_2 monolayers was reported, but this system is characterized by a high density of states at the Fermi level [19]. The novelty of our work in 2*H*-$MoTe_2$ and 2*H*-$MoSe_2$ is that one observes intrinsic long-range magnetic order and at the same time good semiconducting behavior. To fully exploit the magnetic properties of these TMD semiconductors, future work needs to address these important issues.

Importance of the presence of magnetism in semiconducting TMDs

Previously, dilute magnetic semiconductors have been synthesized in a range of thin film and crystal materials [20, 21]. Much interest has been focused on the III-V semiconductor class, where a small concentration of some magnetic ions, particularly Mn^{2+}, can be incorporated by substituting for the group III cations of the host semiconductor. Numerous technical challenges in making uniform DMS materials have been overcome in recent years, but formidable challenges still remain in producing stable, high-quality DMS materials with high T_c. Our present systems offer an alternative route to synthesize DMS materials with the following advantages:

1. The defects contributing to magnetism are intrinsic in the crystal and are uniformly distributed. This can alleviate some of the materials challenges commonly faced in DMS synthesis.
2. The materials are cleavable down to a monolayer thickness and readily grown in large-area form. As it is well established in these materials, the bandgap is strongly dependent on the thickness, providing tunability over the semiconductor properties.
3. The chemical potential and electric field in thin films are easily tuned by electrostatic gates, opening the possibility to tune magnetism, as demons-trated in GaAs.
4. Finally, these materials can be easily layered by van der Waals hetero-epitaxy, allowing the creation of unique new device concepts.

Acknowledgements

ZG: When I discovered magnetism in semiconducting 2*H*-$MoTe_2$ with μSR, I was a postdoc in the Laboratory for Muon Spin Spectroscopy at the Paul Scherrer Institute, Switzerland, working with Dr. Alex Amato and Prof. Elvezio Morenzoni. One month later, with an advanced mobility grant of the SNSF, I joined the group of Prof. Yasutomo Uemura at the Columbia University, where I have carried out systematic studies on these systems in strong collaboration with the group of Prof. Abhay Pasupathy at the Columbia University, Prof. Simon Billinge at the Columbia University and the group of Dr. Elton Santos at the Queens University of Belfast.
AA & ZG: Samples for the initial μSR measurements were provided by Dr. Fabian von Rohr from the University of Zurich. Dr. Daniel Rhodes from the Columbia University provided samples for STM and follow-up μSR experiments. This work benefited from a combination of various experimental techniques and from DFT calculations. The μSR experiments were carried out at the Swiss Muon Source (SμS) of the Paul Scherrer Institute. STM and SQUID experiments were carried out at the Columbia University. DFT calculations were performed at the Queens University of Belfast. X-ray PDF experiments were carried out at the Brookhaven National Laboratory. The authors thank all the people involved in this project.

[1] F. Pulizzi, Nat. Materials **11**, 367 (2012).
[2] O. D. Jayakumar, A. K. Tyagi, Chapter from the book "Functional Materials" *https://doi.org/10.1016/C2010-0-65659-8* (2012).
[3] A. A. Soluyanov *et. al.*, Nature **527**, 495–498 (2015).
[4] X. Xu *et. al.*, Nat. Phys. **10**, 343–350 (2014).
[5] M. N. Ali *et. al.*, Nature **514**, 205–208 (2014).
[6] X. Qian *et. al.*, Science **346**, 1344–1347 (2014).
[7] D. Costanzo *et. al.*, Nature Nanotechnology **11**, 339 (2016)
[8] Z. Guguchia *et. al.*, Nat. Commun. **8**, 1082 (2017).
[9] Z. Guguchia *et. al.*, Sci. Adv. **4**: eaat3672 (2018).
[10] S. Tongay *et. al.*, Appl. Phys. Lett. **101**, 123105 (2012).
[11] C. Ataca *et. al.*, J. Phys. Chem. C **115**, 3934-3941 (2011).
[12] Y. Li *et. al.*, J. Am. Chem. Soc. **130**, 16739–16744 (2008).
[13] A. Amato *et. al.*, Rev. Sci. Instrum. **88,** 093301 (2017).
[14] R. Khasanov, Z. Guguchia *et. al.*, High Press. Res. **36**, 140–166 (2016).
[15] Z. Guguchia *et. al.*, Nat. Commun. **6**, 8863 (2015).
[16] A. Kerelsky *et. al.*, Nano Lett. **17**, 5962–5968 (2017).
[17] Z. Salman *et. al.*, Phys. Rev. Lett. **113**, 156801 (2014).
[18] E. J. G. Santos *et. al.*, New J. Phys. **12**, 053012 (2010)
[19] M. Bonilla *et. al.*, Nature Nanotechnology **13**, 289 (2018).
[20] C. Ding *et. al.*, Phys. Rev. B **88**, 041102(R) (2013).
[21] T. Dietl *et. al.*, Nat. Mater. 9, 965–974 (2010).

Progress in Physics (72)

Ultrathin Layers – Big Effect: Functional Coatings by Plasma Polymerization

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Plasma polymerization defines the process to deposit a so-called "plasma polymer film" (PPF) via activation of a gaseous compound (so-called "monomer") in a low-temperature electrical discharge creating reactive intermediates and film-forming species [1]. These species diffuse to material surfaces yielding film growth at highly non-equilibrium conditions. Functional coatings can thus be applied to a variety of different materials in order to modulate their surface properties. Primary processes in the plasma are activated by electron impact, since mainly the electrons pick up energy from the electric field in collisions with the gaseous particles [2]. The heavy particles thus remain "cold" – defining the low-temperature plasma –, whereas the electrons reach a mean energy of several eV, able to break chemical bonds of the monomer molecule. As a consequence, also compounds that commonly cannot be polymerized, such as for example methane, can be used. The resulting PPFs largely differ from conventional polymers by branching, cross-linking and the lack of repeating units.

Examining the reaction rate in the plasma, i.e. the fragmentation and the resulting deposition rate, the film thickness can be adjusted with high precision at almost atomistic scale. Thus, ultrathin layers, multilayers and nanostructures with vertical gradients can be generated by plasma polymerization.

As another consequence of the mobile electrons, all surfaces in close contact with the plasma get negatively charged with respect to the plasma potential, thus accelerating positive ions towards the surface that gain high energies of tens to hundreds of eV. Accordingly, the highly non-equilibrium, energetic conditions at the surface enables the control over the film density and functionality during film growth – film properties ranging from soft, polymer-like to hard, inorganic coatings are permitted.

Herein, ultrathin plasma polymer layers (with a thickness below about 20 nm) are investigated that serve as an effective barrier to separate a material's surface from the environment, which can be used in different ways to add functionality to the material (Figure 1). As monomers, methane (CH_4) and hexamethyldisiloxane (HMDSO, $(CH_3)_3$–Si–O–Si–$(CH_3)_3$) are discussed in more detail.

The physics behind plasma polymerization

The available energy in the gas discharge, typically represented by the electron energy distribution function (EEDF), allows a plurality of reactions yielding excitation, dissociation and ionization of the monomeric species and their fragments as well as of optionally added carrier and further reactive gases. In-depth understanding and modelling of plasma polymerization processes on a microscopic level thus requires to take account of all involved reaction rates and related cross sections, which are only partially known (Figure 2). For many compounds, however, the film-forming species could be identified due to their high sticking probability, and the corresponding plasma-chemical reaction pathway via dissociation of vibrationally excited states can be predicted.

At typical conditions in a CH_4 plasma with a mean electron energy of 5 eV, for example, approximately hundred times more neutral fragments are observed as ions, since more electrons have energies meeting the threshold energy of ~8 eV for dissociation, whereas ionization starts at ~13 eV with even lower ionization cross sections. Hence, plasma polymerization mainly proceeds via neutral radicals acting as film-forming species.

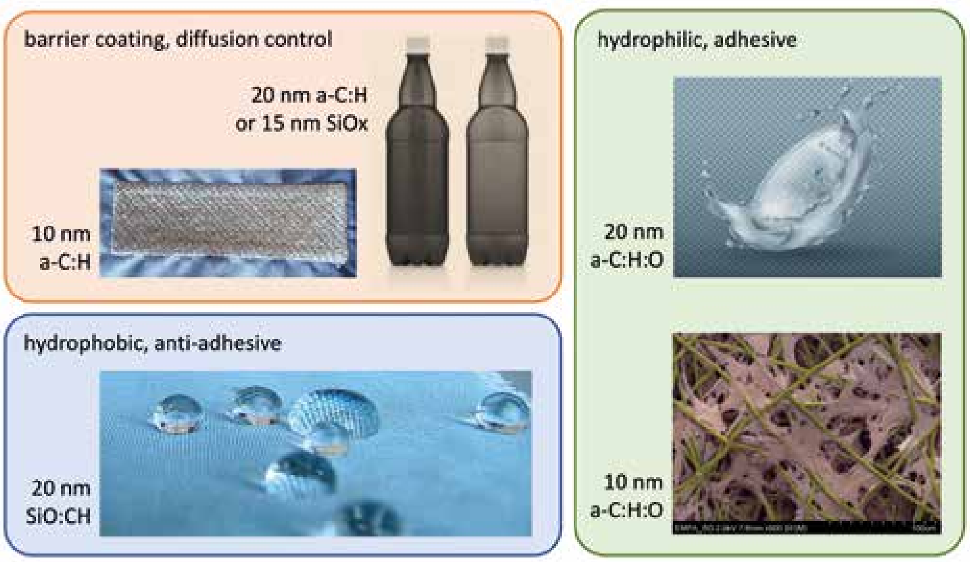

Figure 1. Typical applications for ultrathin plasma polymer films as used for the coating on PET bottles (improving shelf life), textile electrodes (enhancing stability of the electrically conductive Ag-coated yarn), water-repellant fabrics (improving durability and breathability), contact lenses (improving wearing comfort), and tissue engineering (enhancing cell growth on scaffolds).

As a simplified approach, one average reaction rate for the generation of film-forming species might be assumed. Introducing an apparent energy barrier with threshold energy, E_{th}, for activation reactions yielding film-forming species of density, n_{dep}, by electron impact collisions with electron density, n_e, and monomer density, n_m, assuming one averaged collision frequency for activation of the monomer, $\nu_a(E_{th})$, it can simply be noted that

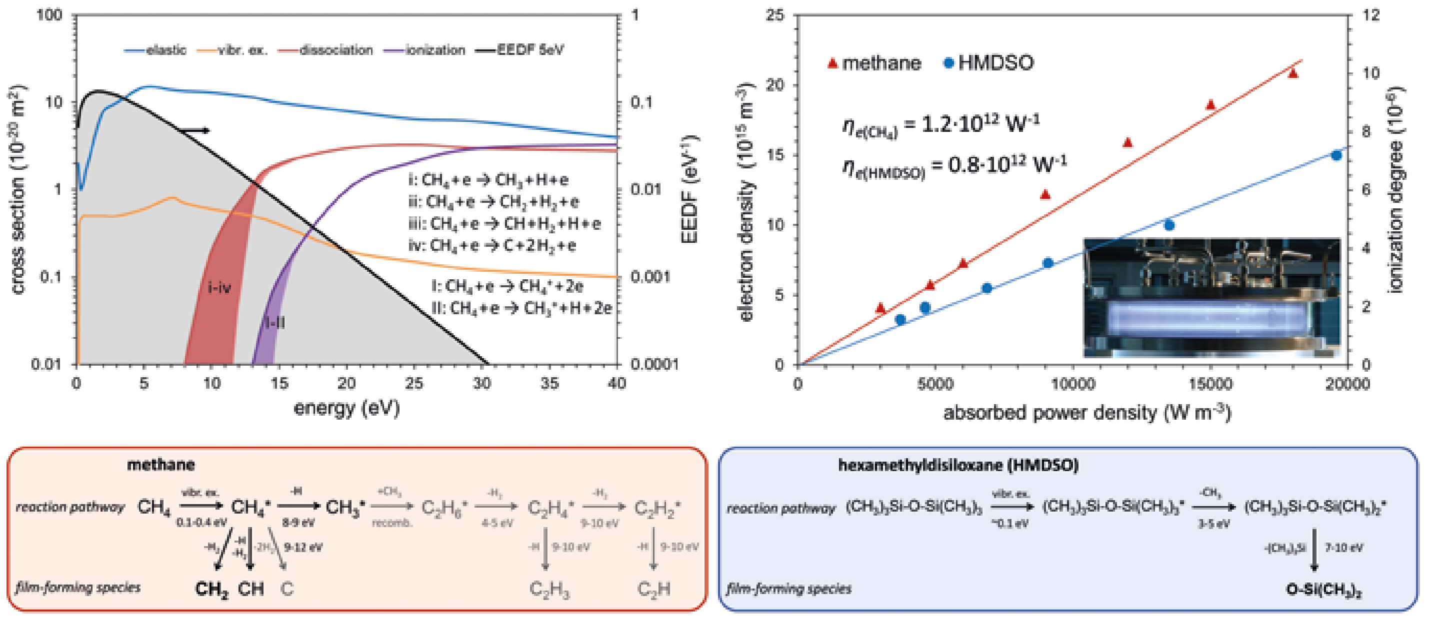

Figure 2. Electron impact reaction cross sections for methane indicating threshold energies for vibrational excitation, dissociation and ionization (left). The grey shaded area gives the electron energy distribution function (EEDF) for a mean electron energy of 5 eV. Electron densities increase linearly with absorbed power density in plasma polymerization processes with a process-depending power coupling coefficient, η_e (right). The inset shows the used capacitively-coupled plasma reactor set-up at a pressure of 10 Pa yielding ionization degrees between 10^{-6} and 10^{-5}. The predicted plasma chemical reaction pathways for methane and HMDSO are added indicating the main film-forming species (below).

$$\frac{dn_{dep}}{dt} = n_e \nu_a \qquad (1)$$

where

$$\nu_a = n_m \langle \sigma_a \cdot v_e \rangle \qquad (2)$$

with the cross section for the overall activation reaction, σ_a, and the electron velocity, v_e [3]. The flux of film-forming species originating from the plasma volume, V_{pl}, towards the deposition area, A_{dep}, can then be given by [2]

$$\Gamma_{dep} = \frac{V_{pl}}{A_{dep}} \frac{dn_{dep}}{dt} = \frac{V_{pl}}{A_{dep}} n_e \nu_a \qquad (3)$$

For polymerizing plasmas with one type of monomer, n_e is typically found to be linear with the absorbed power density, W_{abs} / V_{pl}, in the plasma (see Figure 2):

$$n_e = \eta_e \frac{W_{abs}}{V_{pl}} \qquad (4)$$

introducing the power coupling coefficient, η_e (in [W^{-1}]), that connects microscopic and macroscopic quantities. From Equation (3) and dividing both sides by the monomer gas flow rate, F_m, and normalizing to standard temperature, T_0, and standard pressure, p_0, (k: Boltzmann constant) the (dimensionless) degree of conversion of monomer into film-forming species is given by:

$$c = \frac{kT_0}{p_0} \frac{A_{dep}}{F_m} \Gamma_{dep} = \frac{kT_0}{p_0} \frac{W_{abs}}{F_m} \eta_e \nu_a \qquad (5)$$

The right hand side now contains the well-known reaction parameter, power input per monomer gas flow rate, W/F_m (in [J m^{-3}]), as frequently used for plasma polymerization, which is equivalent to the specific energy input (*SEI*), i.e. the average energy available per monomer molecule in the plasma, E_{pl}, (in [eV]; eE_{pl} in [J] – e: electron charge):

$$SEI = E_{pl} = \frac{kT_0}{ep_0} \frac{W_{abs}}{F_m} \qquad (6)$$

While Γ_{dep} is difficult to assess directly, it is proportional to the mass deposition rate for constant sticking probability, s, and constant molecular mass of the deposited species, M_{dep}, (N_A: Avogadro number):

$$R_m = s \frac{M_{dep}}{N_A} \Gamma_{dep} \qquad (7)$$

Hence, the straightforward evaluation of deposition rates can give important insights into plasma polymerization processes, and the conversion depending on R_m and E_{pl} can be given by combining Equation (5) and (7):

$$c = \frac{kT_0}{p_0} \frac{A_{dep}}{F_m} \frac{N_A}{s\, M_{dep}} R_m = eE_{pl} \eta_e \nu_a \qquad (8)$$

While film-forming species are mainly uncharged highly reactive radicals, the growing film is constantly bombarded by ions such as e.g. CH_4^+ and CH_3^+ in methane or HMDSO plasmas yielding formation of radical sites and densification at highly non-equilibrium conditions [4]. The deposited energy can be obtained from ion flux, Γ_i, and ion energy, E_i, incident on the surface with respect to the deposition rate:

$$E_d = E_i \frac{\Gamma_i}{s\, \Gamma_{dep}} \qquad (9)$$

Film properties such as film density, porosity and functional group density can thus be controlled by adjusting E_d. A minimum energy around 10 eV per condensing molecule is required to create radical sites and covalent bonding to support the formation of highly stable plasma polymer films. Higher energies limit the incorporation of (terminal) functional groups such as $-CH_3$, –COOH, –C-OH etc. due to enhanced crosslinking showing increasing hardness of the PPFs up to ~50 eV per molecule [5]. Even higher deposited energies can result in strong etching conditions.

Plasma polymerization of methane and HMDSO

Commonly used monomers for plasma polymerization comprise CH_4 and HMDSO to deposit amorphous hydrocarbon coatings, a-C:H, and silicone-like coatings, SiO:CH, respectively. To investigate the plasma polymerization processes in depth, a capacitively-coupled plasma reactor has been used that enables a confined uniform plasma volume and well-defined deposition conditions (see Figure 2). The observed deposition rates reveal a linear increase with the average energy per monomer molecule, E_{pl}, up to the threshold energy, E_{th}, which represents the apparent activation energy for the considered plasma polymerization process (Figure 3). Hence, the averaged collision frequency for activation of the monomer, $\nu_a(E_{th})$, appears to be constant for $E_{pl} \leq E_{th}$, according to Equation (8). For $E_{pl} > E_{th}$, the deposition rate starts to saturate revealing an Arrhenius-like behavior depending on E_{pl} instead of temperature, kT, from which E_{th} can be deduced. The corresponding Arrhenius-like fit gives apparent activation energies of ~10 eV for CH_4 and ~13 eV for HMDSO, which is in excellent agreement with the predicted overall reaction pathway to generate film-forming species (see Figure 2 and 3). The process conditions can thus be adjusted to allow sufficient fragmentation in the gas phase, while controlling deposition rates by F_m and E_{pl}.

The used reactor set-up and pressure (10 Pa) yields a maximum conversion of monomer into film-forming species of 30 - 40 % assuming a sticking probability around one at sufficient energy provided for film growth. The conversion could be further enhanced by raising the power coupling coefficient, e.g. by reducing pressure, adding carrier gases (Ar) or using different plasma sources such as inductively-coupled and microwave plasmas.

Considering surface conditions with moderate E_d around 10 - 20 eV, polymer-like a-C:H and SiO:CH films are formed, whereby the film density increases with E_d from about 1.1 to 1.5 g cm^{-3} [6]. In this way, the permeability and hydrophobicity of such PPFs can be controlled for barrier coatings and water-repellency on soft, polymeric substrates such as PET bottles or textiles [6-8]. In order to observe continuous closed films, a thickness of around 10 - 20 nm is required allowing fast processing with coating times as low as 2 s [7].

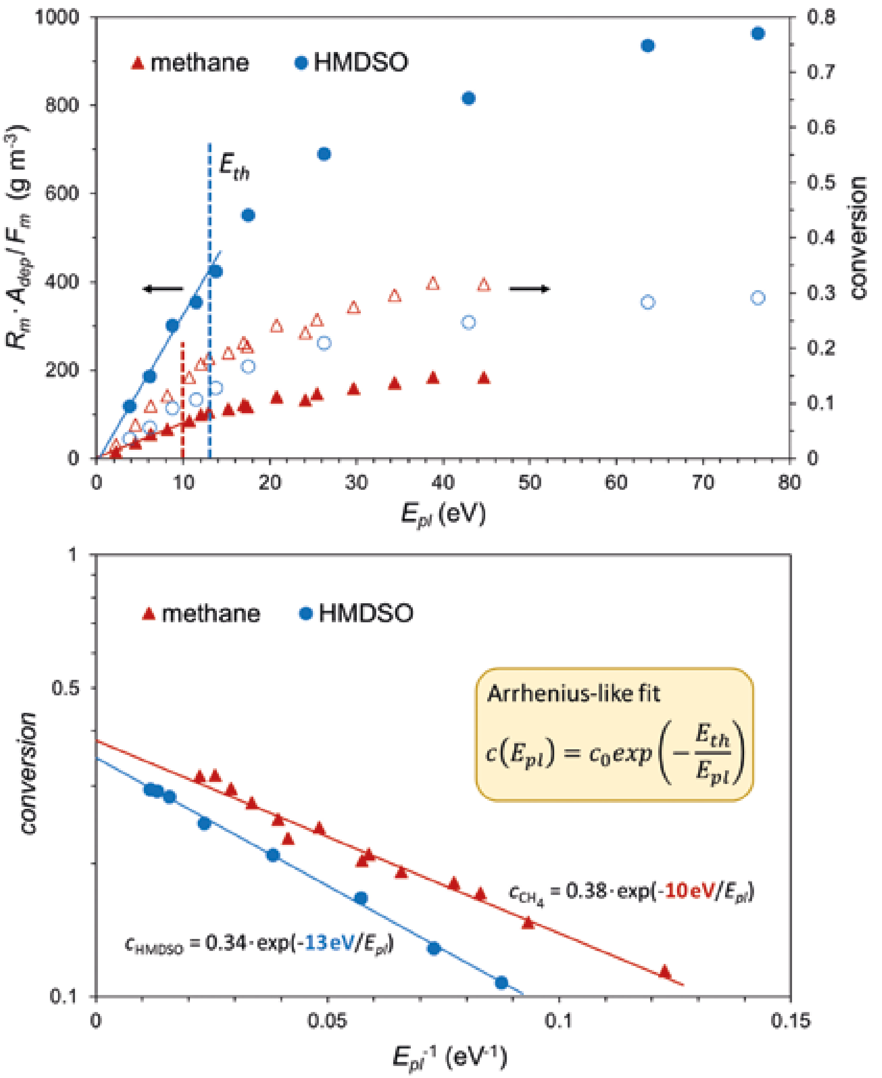

Figure 3. Normalized deposition rates for CH_4 and HMDSO plasmas showing a linear increase with the energy invested per monomer particle, E_{pl}, up to a threshold energy, E_{th} (top). While the absolute deposition rates are higher in HMDSO due to larger film-forming species, the conversion, i.e. the percentage of monomer molecules incorporated into film growth, is comparable (open symbols). The conversion at higher energies reveals an Arrhenius-like behavior, where temperature, kT, is replaced by E_{pl} (bottom). The apparent threshold energies for plasma polymerization can thus be deduced yielding ~10 eV for CH_4 and ~13 eV for HMDSO.

Besides the control of energy input, film properties can strongly be influenced by gas composition, e.g. by addition of oxygen in the plasma. Gas ratios of O_2 / CH_4 ≤ 1 result in highly functional nanolayers of a-C:H:O PPFs that, for example, increase the wearing comfort for contact lenses manufactured at low costs in a dry and environmentally friendly process [9]. Likewise, the wettability and adhesion properties can be enhanced, e.g. for biomedical applications [10, 11]. Oxidation of HMDSO, on the other hand, requires higher O_2 / HMDSO ratios in order to oxidize the hydrocarbon side groups as well as the side products, the SiC_3H_9 radicals, ideally yielding two SiO_2 film-forming units per HMDSO molecule [12]. High oxidation and densification yields ultrathin SiO_2-like PPFs that are used as barrier coatings on PET bottles and further packaging materials.

Very recent activities concern the initial adsorption of proteins as well as bacterial adhesion on surfaces, where the deposition of a 2 nm thick SiO:CH coating from a HMDSO plasma serves as a cover layer separating the substrate material from the biological medium. For the protein experiments with bovine serum albumin (BSA), the cover layer was deposited on a nanoporous SiO_x base layer, i.e. less densified as a barrier coating, thus providing a hydrophilic subsurface structure. Interestingly, it was observed that the protein adsorption is affected by water intrusion through the cover layer depending on the free volume, i.e. the porosity, of the subsurface [13]. Formation of fixed dipoles due to trapped water molecules might induce an additional long-range interaction that can be exploited to control initial protein adsorption independent of surface properties. For the bacterial adhesion with *E. coli*, the 2 nm SiO:CH cover layer was deposited on silicone elastomers showing varying stiffness by modifying the PDMS:crosslinker ratio. It has been controversially discussed whether the viscoelastic properties of a material influence bacterial adhesion yielding stronger adhesion on softer material. The ultrathin plasma layer maintained the viscoelastic properties by equalizing the surface properties. As an important finding, bacterial adhesion was found to hardly depend on viscoelastic properties but on the stickiness of the surface [14].

Conclusion

Plasma polymerization, i.e. the generation of film-forming species in a low-temperature plasma, can be controlled by gas composition as well as the energy available per monomer molecule in the gas phase and during film growth at the surface. Thus, ultrathin coatings can be deposited with high precision on a variety of substrate materials enabling functional surfaces with tailored properties by fast, economic and sustainable processes.

References

[1] H. Biederman, *Plasma Polymer Films*, Imperial College Press, London, UK 2004.
[2] J. Reece Roth, *Industrial Plasma Engineering*, Inst. Phys. Publ., Bristol, USA 2001.
[3] D. Hegemann, *J. Phys. D: Appl. Phys*. **46**, 205204 (2013).
[4] D. Hegemann, B. Hanselmann, N. Blanchard, M. Amberg, *Contr. Plasma Phys*. **54**, 162–169 (2014).
[5] S. Peter, K. Graupner, D. Grambole, F. Richter, *J. Appl. Phys*. **102**, 053304 (2007).
[6] D. Hegemann, Plasma Polymer Deposition and Coatings on Polymers. In: *Comprehensive Materials Processing*, Vol. 4, Ed. D. Cameron, Elsevier Ltd., 2014, pp 201–228.
[7] A. Shirakura, Ma. Nakaya, Y. Koga, H. Kodama, T. Hasebe, T. Suzuki, *Thin Solid Films* **494**, 84 (2006).
[8] M. Amberg, M. Vandenbossche, D. Hegemann, *Surf. Coat. Technol* **336**, 29 (2018).
[9] H. Yasuda, Y. Matsuzawa, *Plasma Process. Polym*. **2**, 507 (2005).
[10] F. Awaja, S. Zhang, N. James, D. R. McKenzie, *Plasma Process. Polym*. **7**, 1010 (2010).
[11] A. G. Guex, F. M. Kocher, G. Fortunato, E. Körner, D. Hegemann, T. P. Carrel, H. T. Tevaearai, M. N. Giraud, *Acta Biomater*. **8**, 1481 (2012).
[12] M. Deilmann, H. Halfmann, S. Steves, N. Bibinov, P. Awakowicz, *Plasma Process. Polym*. **6**, S695 (2009).
[13] E. Bülbül, P. Rupper, T. Geue, L. Bernard, M. Heuberger, D. Hegemann, *ACS Appl. Mater. Interfaces* **11**, 42760 (2019).
[14] F. Pan, S. Altenried, M. Liu, D. Hegemann, E. Bülbül, J. Moeller, W. W. Schmahl, K. Maniura-Weber, Q. Ren, *Mater. Horiz.* DOI: 10.1039/C9MH01191A (2019).

Progress in Physics (73)

Magnetic Skyrmions: From Fundamental Physics to Topological Electronics

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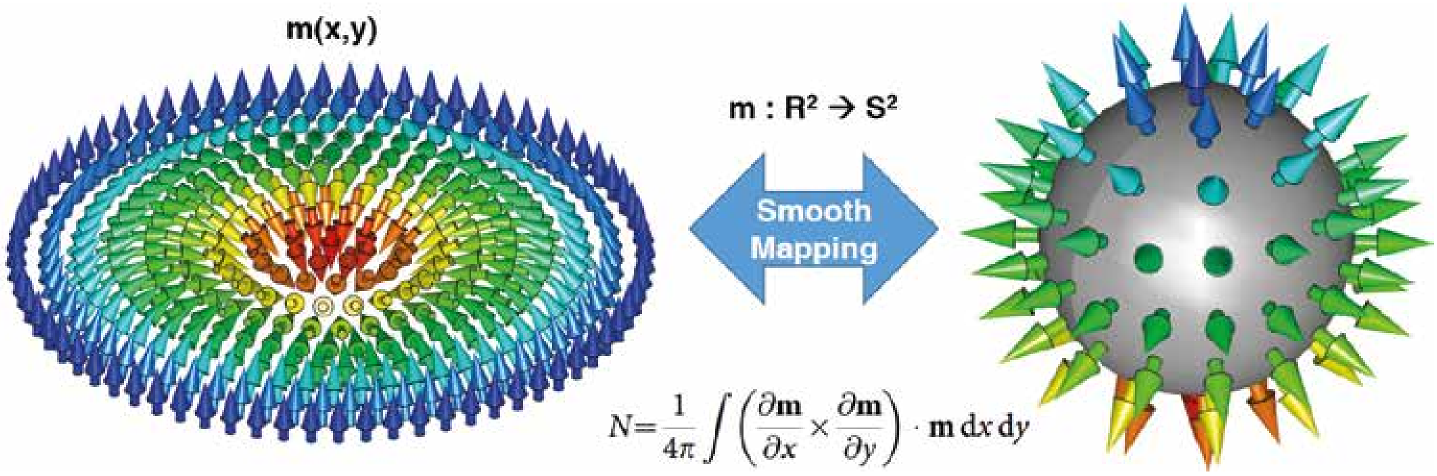
Introduction

In the 1960s, the high-energy theorist Tony Skyrme was seeking a field theoretical description for the stability of hadrons [1]. By considering a continuous quantum field in the presence of a non-linear excitation, he showed that protons and neutrons could emerge as soliton-like excitations of a spinless pion medium. Skyrme's new concept was that the particle stability could arise by considering the excitation (later dubbed the skyrmion) as a quantized topological de-



$$N=\frac{1}{4\pi}\int\left(\frac{\partial \mathbf{m}}{\partial x}\times\frac{\partial \mathbf{m}}{\partial y}\right)\cdot\mathbf{m}\,dx\,dy$$

Figure 1: Left shows a schematic visualization of a skyrmion that can be found in magnetic materials, where arrows depict the local direction of the magnetization m. Right shows the result of mapping of the real-space magnetization distribution to an order-parameter space described by the surface of a three-dimensional sphere. The inset integrand provides a convenient means to determine if the real-space magnetization distribution completely wraps the order parameter space, with |N| = Z > 0 describing topological magnetic structures.

fect of the background field. While Skyrme's proposal does not form part of modern mainstream particle physics, his principles nonetheless find traction in various branches of condensed matter physics, ranging from quantum Hall systems, liquid crystals, Bose-Einstein condensates and, as we discuss here, magnetic materials.

In magnetic systems, the skyrmionic excitation can be considered as a topological defect of an otherwise uniform magnetization field. As shown on the left in Figure 1, the skyrmion is visualized in a two-dimensional plane as a point-like region of magnetization reversal at the centre surrounded by a whirl of twisted magnetic spins. Translational invariance is assumed along the third dimension. The topological aspect of the skyrmionic magnetization texture is understood conceptually by examining the mapping of the real-space spin structure to a spherical order parameter space. When the physical space of the magnetization fully wraps the order parameter space at least once - see the right side of Figure 1, the topological winding number is a finite integer and the magnetization texture is described as topologically nontrivial. This condition is never satisfied for topologically trivial magnetization textures such as simple ferromagnets and Néel antiferromagnets, making skyrmions a topologically distinct form of magnetism.

Thus, in the spirit of Skyrme's original proposal, skyrmions in magnets can be considered as closed, individually countable particle-like states that display a robustness to perturbation due to their distinct topology with the background field. It is these fascinating properties - all rooted in the topology of skyrmions - that make skyrmions not only of fundamental interest, but suitable as robust elements of potential applications such as information carriers or non-volatile storage elements. Accordingly, these reasons motivate the substantial worldwide research effort into skyrmion hosting systems. In Switzerland the National Science Foundation recently funded a network on Nano-Skyrmionics [https://skyrmions.epfl.ch] joining scientists from various institutions. Here, we provide a status report on selected forefront aspects of the research field. This includes identifying fundamentally new topological magnetization configurations, the processes of skyrmion nucleation, manipulation, annihilation and detection with a view to their application as parts of memory devices, and their potential integration in broad-band spin dynamic and logic devices.

Skyrmions in non-centrosymmetric magnets

The twisted magnetization distribution of magnetic skyrmions indicates multiple magnetic interactions are required for their stability. In the late 1980s to the 2000s, pioneering theory showed that the right interaction schemes could be found in magnetic crystals with a strong Heisenberg exchange J - which favours a collinear magnetization as for ferromagnetism - and a weaker but competing Dzyaloshinskii-Moriya interaction (DMI), D due to spin-orbit coupling that favours a perpendicular spin arrangement [2-5]. Due to the competing effect of the weaker DMI, a gradual twisting of the otherwise collinear magnetization required for skyrmions can be naturally achieved. Moreover, the skyrmion size λ is approximately determined by the ratio $\lambda \sim D/J$, and it typically ranges from 1 to 100 nm. Thus the DMI emerges as the key ingredient for skyrmion formation in the vast majority of the known host systems.

For bulk magnets, the DMI can be introduced into the Hamiltonian when the atomic structure has no inversion symmetry. These noncentrosymmetric crystals can be classified according to their point group symmetries, which in turn dictate the pattern of the allowed DMIs and ultimately the internal magnetization texture of the skyrmion [2,3]. Figure 2 shows schematics of the different types of magnetic skyrmion discovered up to now.

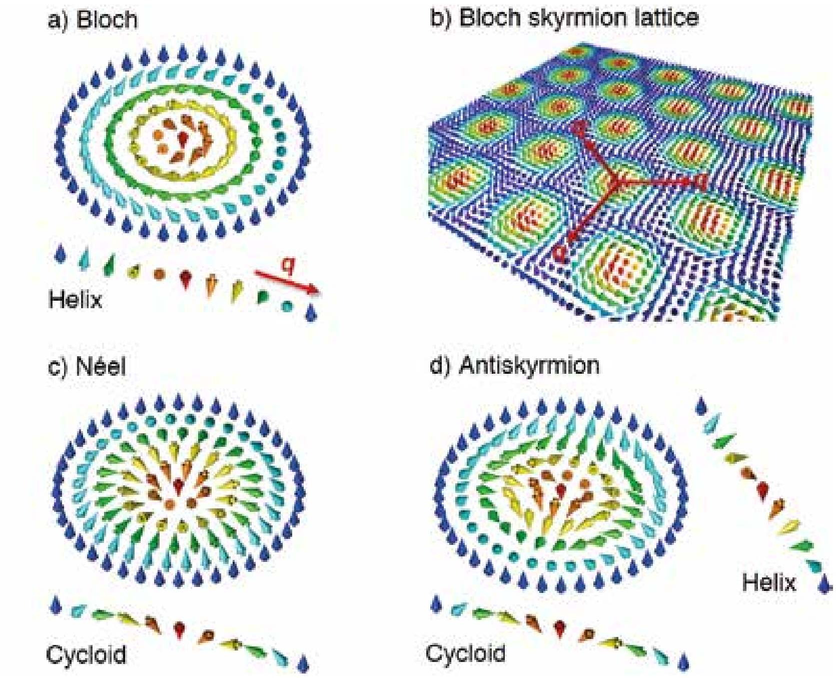


*Figure 2: Schematics of the known skyrmion types and a skyrmion lattice. a) Bloch-type skyrmion which has an inherent helix modulation. b) A Bloch-type skyrmion lattice approximately described in terms of three propagation vectors **q** (a so-called triple-q structure). c) Sketch of a Néel-type skyrmion with an inherent cycloid modulation, and d) an Antiskyrmion with inherent helix and cycloid modulations. Panel (b) is © Yoichi Nii.*

The Bloch-type skyrmion shown in Figure 2a is the most common found in the bulk, in particular in crystals described by chiral point groups. Indeed, the Bloch skyrmion was the first type to be discovered in 2009, being shown by small-angle neutron scattering (SANS) to form a hexagonal skyrmion lattice in the then-mysterious *A*-phase of the *B*20 chiral cubic magnet MnSi with spacegroup $P2_13$ [6]. This system was already well-known for its helix ground state (lower part of Figure 2a) described by one propagation vector ***q***, and which onsets immediately on cooling below the critical temperature T_c = 29 K. The SANS experiment showed the *A*-phase in MnSi - which it turns out is archetypal for many skyrmion materials by being thermodynamically stable just a few Kelvin below T_c and in a small magnetic field - to be a skyrmion lattice phase. Here the skyrmion lattice can be described approximately by a superposition of three helices to form a so-called triple-***q*** structure (Figure 2b). Shortly afterwards in 2010 [7], the hexagonal skyrmion lattice structure was confirmed by real-space Lorentz transmission electron microscopy (LTEM) studies of $Fe_{0.5}Co_{0.5}Si$, another *B*20, $P2_13$ system. In this study isolated skyrmions were also observed directly, emphasizing their inherently particulate nature.

Over the last decade, the types of magnetic crystal found to host skyrmions has diversified far beyond *B*20 compounds. In 2012, the $P2_13$ system Cu_2OSeO_3 was discovered to display an *A*-phase that hosts Bloch skyrmions below $T_c = 57$ K [8]. Unlike the *B*20s which are generally metallic or semiconducting, Cu_2OSeO_3 is an oxide insulator with pronounced magnetoelectric coupling and suppressed spin wave damping. These latter properties offer unique perspectives for control of the static and dynamic properties of skyrmions in insulators in contrast to metallic systems. Later in 2015, Bloch skyrmion lattice phases were discovered for the first time to be thermodynamically stable at room temperature in the itinerant $Co_8Zn_8Mn_4$ alloy with chiral cubic spacegroup $P4_132$ or $P4_332$ [9,10]. By tuning the composition of the Co-Zn-Mn alloy the temperature range of thermodynamic skyrmion phase stability can be shifted either well above or well below room temperature. Notably, in $Co_9Zn_9Mn_2$ metastable skyrmion states have been realized at room temperature and zero magnetic field [11].

Also in 2015, the Néel-type skyrmion lattice (Figure 2c) was discovered in the polar semiconducting spinel GaV_4S_8 with spacegroup *R*3m [12]. The Néel-type skyrmion lattice form can be described as a superposition of three cycloidal modulations. Finally in 2017, a novel 'antiskyrmion' texture (Figure 2d) was discovered by LTEM at room temperature in a Heusler alloy $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$, spacegroup $I\bar{4}2m$ [13]. In this system the complex DMI pattern leads to an internal magnetization texture with inherent cycloid and helix modulations.

As introduced here, a variety of non-centrosymmetric magnets have been discovered to host various types of skyrmionic spin textures, including some at room temperature. Nonetheless, current efforts in materials discovery continue unabated, aiming at diversifying further the classes of known topological spin textures and host systems. From a fundamental perspective, the motivation is to expand the number of skyrmion phases and hence platforms for exploring the fundamental physics of topologically non-trivial magnetism, in either thermodynamic equilibrium phases or far-from-equilibrium metastable states. From an applications perspective, the achievement of skyrmions with new internal magnetization textures, particularly at room temperature and across metallic and insulating systems, promises versatile and distinct functionalities. In addition to the bulk noncentrosymmetric magnet skyrmion systems mentioned above, skyrmions can be realized in fabricated magnetic multilayers, which will be described later in this article.

Skyrmion creation and manipulation in thin plates of non-centrosymmetric magnets

In bulk skyrmion hosting materials, the underlying magnetic state is not a ferromagnetic state, but a modulated helical

How to measure skyrmions

There exist several experimental methods with which skyrmions can be detected.

Small angle neutron scattering (SANS): Just like X-ray diffraction can be used to measure crystalline structures, neutron scattering can be used to measure magnetic structures in accordance with Bragg's law $n\lambda = d \sin(\theta)$. A triangular lattice of skyrmions gives rise to a characteristic 6-fold pattern of Bragg peaks on the neutron detector, as illustrated in figure A1. SANS was used to identify skyrmions first in MnSi [6], and subsequently in a growing number of skyrmion hosting materials.

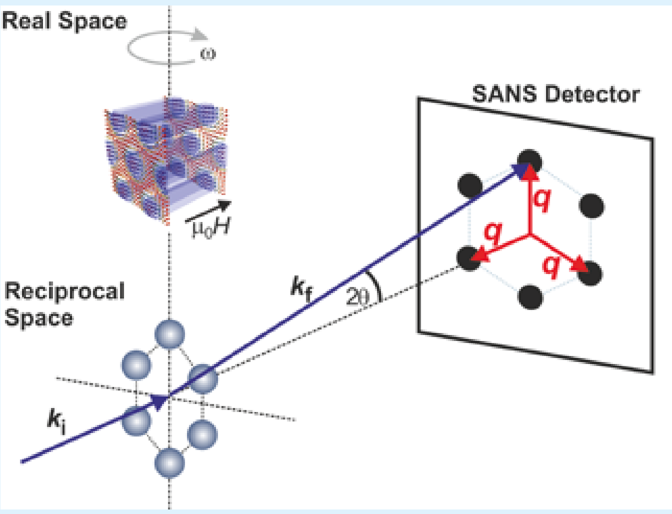


*Figure A1: Schematic showing how neutrons diffracting off the two-dimensional hexagonal skyrmion lattice in real-space, results in a six-fold ('triple-**q**') skyrmion lattice diffraction pattern on the SANS detector. To observe the hexagonal pattern, the magnetic field, which defines the direction of the skyrmions, is aligned approximately with the neutron beam wavevector $\mathbf{k}_i$.*

Magnetic contrast, Lorentz, transmission electron microscopy (LTEM): In a transmission electron microscope, electrons travel through a thin (few hundred nm) sample. The in-plane component of a magnetization pattern deflects the electrons perpendicular to the magnetization direction - this is known as the Lorentz force. Since

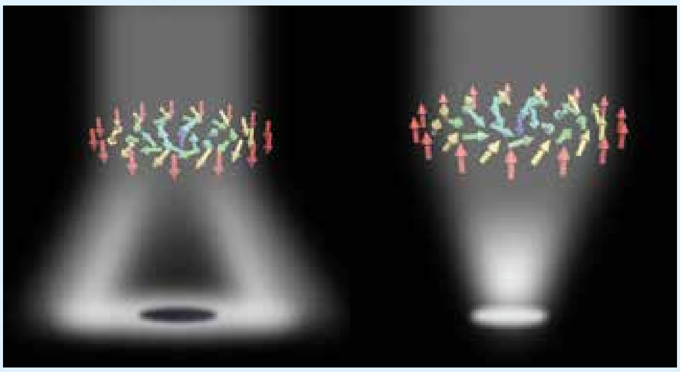


Figure A2: Illustration of how the circulating in-plane magnetization component of a skyrmion respectively focuses or defocuses the electron beam depending on the sense of rotation (chirality) of the skyrmion. (In detail, because an electron microscope employs focusing optics, the effect of the skyrmion is to change the effective focal length for magnetic contrast.)

the in-plane component of the skyrmion has the magnetization circling in a ring around its center, a skyrmion will act as a focusing or defocusing lens for the electrons. Hence, LTEM images skyrmions as well defined dots in the image. This special phenomenon makes real-space studies of skyrmions a very powerful and exciting field of research.

Topological Hall effect (THE): When current carrying electrons flow through a material in presence of a magnetic field, the Lorentz force bends their trajectory leading to a transverse potential - a phenomenon known as the Hall effect. (Some two-dimensional electron systems exhibit a special quantum Hall effect, which was the topic of the 1985 and 1998 Nobel prizes in physics, and in 2019 was used for redefining the international system of units [14]). In ferromagnetic materials, the external magnetic field is amplified by the local magnetization leading to a much stronger anomalous Hall effect, which is proportional to the magnetization of the sample. The special topological nature of the skyrmion spin texture leads to a different topological Hall effect. Therefore, the possible existence of skyrmions can be inferred by comparing measurements of Hall effect and magnetization as a function of magnetic field. Since such measurements are easier and cheaper than neutron scattering (which requires large samples) or electron microscopy (which require micro-fabrication of the sample), topological Hall effect often gives the first hint of skyrmions in a new material.

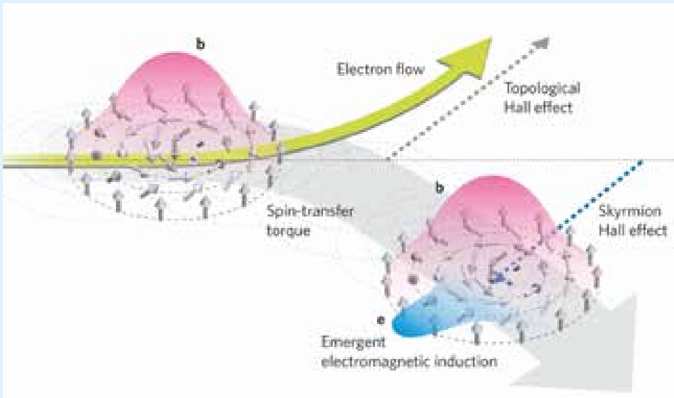


Figure A3: Schematic of the topological Hall effect, adapted from [15].

Broadband microwave spectroscopy on collective spin excitations: Wave-impedance matched transmission lines or coplanar waveguides optimized on dielectric substrates (Fig. A4) are widely exploited to investigate collective spin excitations in skyrmions crystals. Using for instance the output port of a vector network analyzer (VNA) one applies a frequency-tunable microwave current to the metallic leads which generates a microwave magnetic field at the position of the skyrmion-hosting magnetic material. Thereby the non-collinear spin structure experiences a torque and undergoes spin-precessional motion. Via the time-dependent magnetic flux density and Henry-Faraday's induction law the precessing spins induce a microwave signal in the metallic conductor whose phase and amplitude are analyzed in the detector input of the VNA. Such broadband microwave spectroscopy setups have allowed for the resonant excitation and detection of the magnetization dynamics in skyrmion crystals and further collinear and non-collinear spin structures. Several theoretical and experimental groups showed independently that periodic lattices of skyrmions exhibit a characteristic set of eigenmodes. Their field dependencies and polarization characteristics nowadays serve as a fingerprint of a skyrmion phase which can be tested inductively and non-invasively without attaching e.g. electric leads.

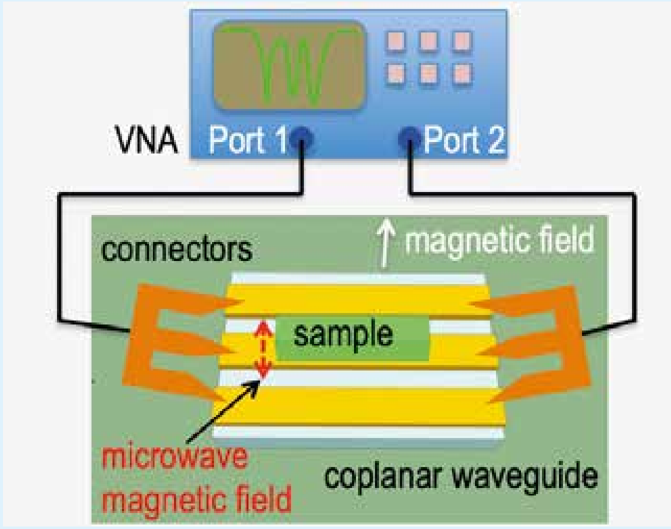


Figure A4: The spin structure of a magnetic sample is excited using a microwave current applied to a coplanar waveguide.

Scanning transmission x-ray microscopy (STXM): High resolution imaging gives an important insight into the physics of skyrmion systems. STXMs are synchrotron based instruments working in the soft x-ray range (typically 200 - 2000 eV) covering the L-edges of the transition metals and the M-edges of the rare earth elements. The spatial information is obtained by focusing an x-ray beam using Fresnel zone plates to a spot of typical 20 - 30 nm and raster scanning the sample through this spot. The transmitted intensity is recorded to generate an image [16]. In addition x-ray magnetic circular dichroism provides element specific magnetic contrast, as the x-ray absorption depends on the relative orientation of the magnetization with respect to the polarization vector, if the photon energy is tuned to the respective absorption edge of the magnetic element of interest. Figure A5 shows a sketch of a STXM and an example image of skyrmions.

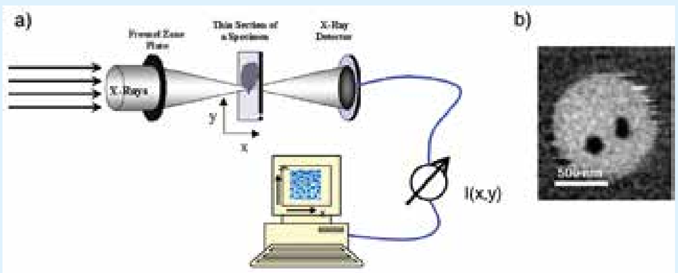


Figure A5: a) Sketch of a scanning transmission x-ray microscope (STXM). b) Example of a magnetic image of two skyrmions in a disk of a magnetic multilayer, the grey level corresponds to out-of plane component of the magnetization (m_z).

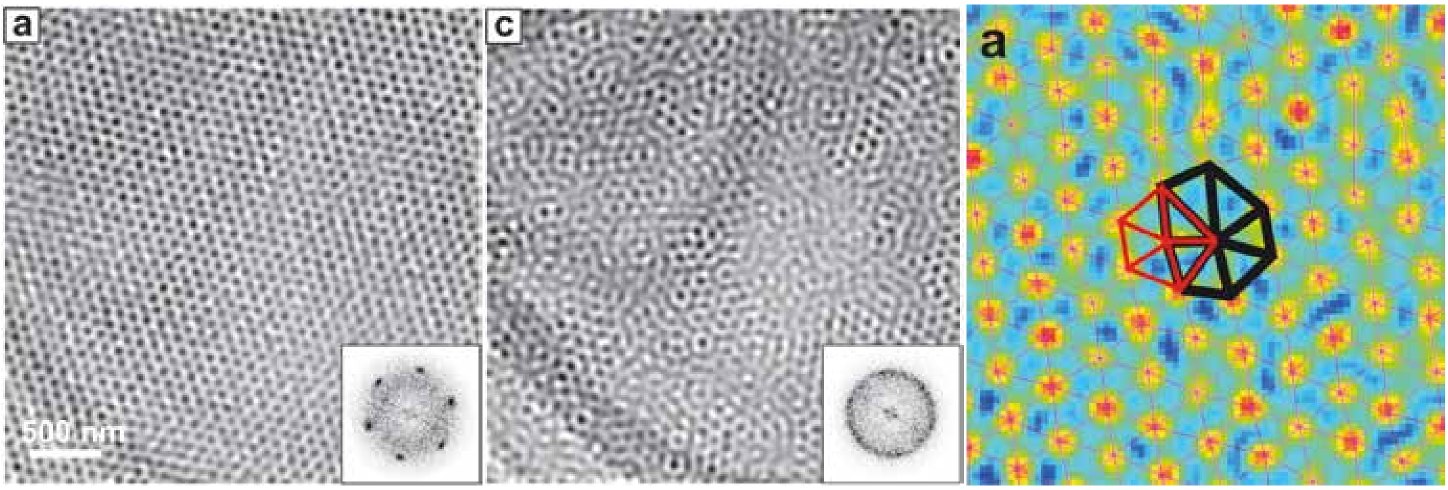


Figure 3: (left and middle) Skyrmion solid and skyrmion liquid imaged with magnetic contrast electron microscopy LTEM, from [17], (right) 5-7 defect from [18].

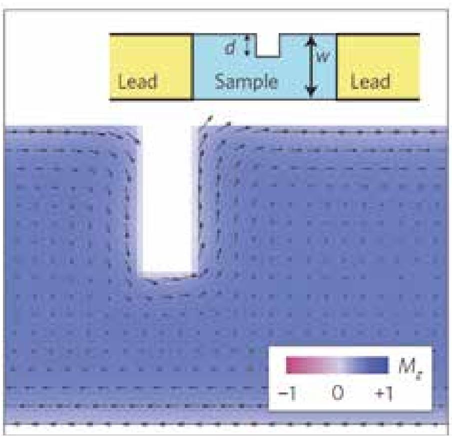
or cycloidal structure with a well defined periodicity $\lambda \sim D/J$. Therefore, the skyrmions are strongly bound in a triangular lattice with distance λ, and it is difficult to observe isolated skyrmions. One might therefore speculate whether these magnetic textures are best described as ordering of topologically protected skyrmion particles or simply as a magnetic structure composed of 3 superposed helical modulations. Studies of defects and dynamics of the magnetization pattern partly answers this question. Defects and dynamics in a 3q structure would involve fluctuations in the direction, periodicity and relative phases of the 3 propagating helices. However, what is observed experimentally is that the skyrmions remain well defined and move around like particles even when the lattice is disordered into a skyrmion liquid [17]. Thus, defects in the magnetization pattern are limited to well defined defects of the triangular lattice. These observations on the one hand demonstrate that the skyrmions are topologically protected as emergent particles, but on the other hand imply that also the lattice of skyrmions exhibits topologically defined dynamics. The 2016 Nobel prize in physics was awarded to Kosterlitz, Thouless and Haldane for introducing topological concepts to condensed matter physics. Specifically, Kosterlitz and Thouless discovered that in 2D the phase transition between a solid and a liquid is topological in nature and is characterized by the formation and eventual unbinding of defect pairs. In the triangular lattice where every site should have 6 neighbours, the defect pair has respectively 5 and 7 neighbours. Phase transitions involving atoms or molecules are difficult to image directly due to the required spatial and temporal resolution.With the ability of electron microscopy to image and record movies of large areas with up to 10^5 skyrmions, skyrmions have surprisingly emerged as a new platform for experimental real-space studies of such 2D topological phase transitions.

Studies of skyrmion dynamics are not limited to studying intrinsic fluctuations. Many studies have explored driving and controlling the skyrmions. In MnSi it was found that skyrmions can be driven by current densities as low as 1 μA/μm^2, which is 5 orders of magnitude less than for magnetic domain walls [19]. The phenomenon was explained through spin-transfer-torque by the polarized electron flow and a quantitative theory was developed [20,21]. The rather low pinning of skyrmions was investigated both with resistance noise spectroscopy [22], where the washboard effect frequency of the regular skyrmion lattice sliding past fixed pinning centres allowed extracting skyrmion drift velocities of 1 - 100 μm/s, and with in-situ SANS [23], which revealed increased pinning at the edges of the material, leading to hydrodynamic-like flow of skyrmions.

Part of the rapidly growing interest in magnetic skyrmions is driven by the potential of information storage. To this end controlled creation of skyrmions is required. It has been proposed theoretically that driving a current past a notch constriction can generate individual skyrmions from a uniformly magnetized state [24], and demonstrating experiments are ongoing. Several other mechanisms have been proposed [25], some of which have been realized experimentally for bulk systems, including use of electric fields in the insulating skyrmion hosting material Cu_2OSeO_3 [26] and laser pulses in the near-room-temperature skyrmion hosting compound FeGe [27]. So far skyrmion creation in bulk materials has mainly resulted in transition to the skyrmion lattice state rather than controlled creation of single or few skyrmions. In this respect, efforts in multilayer magnetic films have progressed further as will be discussed later in this article.

Collective excitations of magnetic skyrmions

Soon after the discovery of its surprising quasistatic properties a pioneering micromagnetic simulation study performed by M.



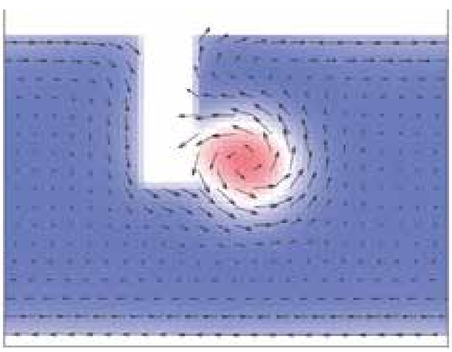


Figure 4: Simulation of how a notch in a current carrying strip can nucleate individual skyrmions. Adapted from [24].

Mochizuki showed that a skyrmion crystal exhibited characteristic dynamic excitations [28]. The three collective spin excitations were classified concerning their peculiar spin-precessional motion and named correspondingly as breathing, clockwise and counterclockwise rotational modes. Mounting the chiral ferrimagnetic insulator Cu_2OSeO_3 on a conventional microwave antenna and performing broadband microwave spectroscopy at cryogenic temperatures Y. Onose *et al*. indeed observed magnetic resonance phenomena consistent with the predicted polarization characteristics and character of spin-precessional motion in a skyrmion lattice [29]. Several other groups performed similar microwave experiments afterwards and evidenced that the three modes represented a universal feature, no matter whether the skyrmion crystals appeared in metallic, semiconducting or insulating magnetic materials. Still their exact resonance frequencies varied from material to material between roughly about 1 and a few 10 GHz. These observations were in agreement with a recently developed theory which also considered the specific shapes of the magnets [30]. The characteristic set of field-tunable resonances in the few GHz frequency regime stimulated the broader interest in skyrmion-hosting materials concerning the exploration of their novel functionalities for signal processing at microwave frequencies which are relevant for information technologies and mobile communication.

Skyrmions in magnetic multilayers

Magnetic multilayer stacks (MML) were long used to provide systems with a perpendicular magnetic anisotropy (PMA) and they are used e.g. to study magnetic bubbles. By introducing asymmetries around the magnetic layers by choosing different non-magnetic heavy metal layers an asymmetric exchange, the DMI is introduced into these systems, providing the necessary requirements for stabilizing skyrmions. Here, the DMI is an interface effect, strongly depending on the materials combination selected. One example of the experimental realization of these stacks are Co/Pt/Ir, shown in Figure 5. The strength of this effect depends on the materials used in these multilayer stacks, illustrated in Figure 6. This explains why one of the routinely used material systems Co/Pt/Ir shows a large DMI. The different signs of the two interfaces, the Co/Pt and the Co/Ir interface add up in absolute value, as they sit on opposite sides of the film, resulting in an inversion of the sign for one of them.

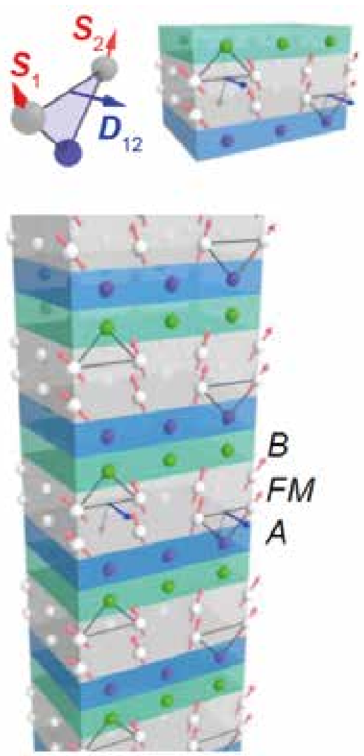


Figure 5: Interfacial Dzyaloshinskii-Moriya interaction (DMI) in asymmetric magnetic multilayers. The DMI for two magnetic atoms (gray spheres) close to an atom with large spin-orbit coupling (blue sphere). Zoom on a single trilayer composed of a magnetic layer (FM, gray) sandwiched between two different heavy metals A (blue) and B (green) that induce the same chirality (same orientation of D) when A is below and B above the magnetic layer, and finally on an asymmetric multilayer made of several repetition of the trilayer. (Figure adapted from [31])

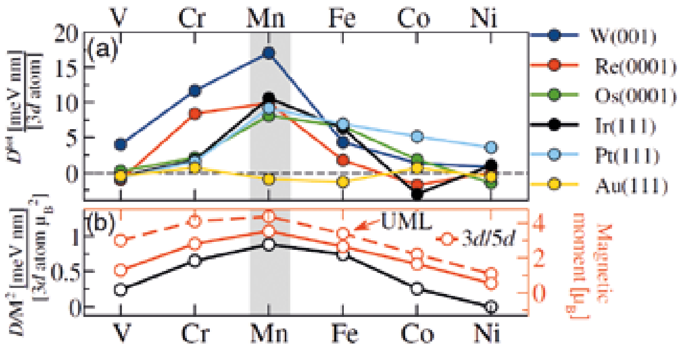


Figure 6: Strength of the DMI for different material combinations, derived from first-principle calculations. (Figure taken from [32], with permission from APS). Strength and sign of the Dzyaloshinskii-Moriya interaction D^{tot} in 3d TM monolayers on 5d substrates calculated around their magnetic ground. A positive sign of D^{tot} indicates a left-rotational sense or "left chirality".

For various applications, MML based skyrmion systems are very promising, as they allow to tune the properties to the actual needs. Important features are stability at room temperature and at zero field. Current research is focusing on various aspects, which are important for applications, e.g. the defined creation, manipulation and detection of skyrmions. For the creation in a confined region, current induced nucleation processes, as shown in Figure 7, are very promising.

Towards applications these Skyrmions have to be manipulated and detected. For the manipulation, e.g. shifting skryrmions through structures, current driven processes are very good candidates, as they are well compatible with existing electronic concepts. One example is presented in e.g. [34], where skyrmion velocities of several ten meters per second were archived. Finally the presence of skyrmions has to be detected, e.g. for reading out a logic state from a signal processing system. Candidates for a link of skyrmion system to electric circuits are the skyrmion Hall effect [35] or magneto resistive effects, like the tunnel magneto resistance, as they are nowadays also used in magnetic storage devices.

Skyrmions for applications

As introduced in the previous sections, skyrmions attract enormous interest in the context of their potential use as high-speed information carriers with low energy consumption. This expectation received the initial impetus from pioneering experimental work on the skyrmion phase in MnSi, both by SANS in 2010 [19] and Topological Hall effect (THE) measurements in 2012, [36]. In these experimental studies the Bloch-type skyrmions were observed to be depinned and driven into motion by application of an ultralow threshold electric current density of 10^6 A·m^{-2}. On the one hand, since this threshold current density is 5 orders smaller than that required to depin ferromagnetic domain walls, the expectation for using skyrmions in low power spintronic devices was ignited and continues unabated. On the other hand, under such a low depinning current density, the skyrmions

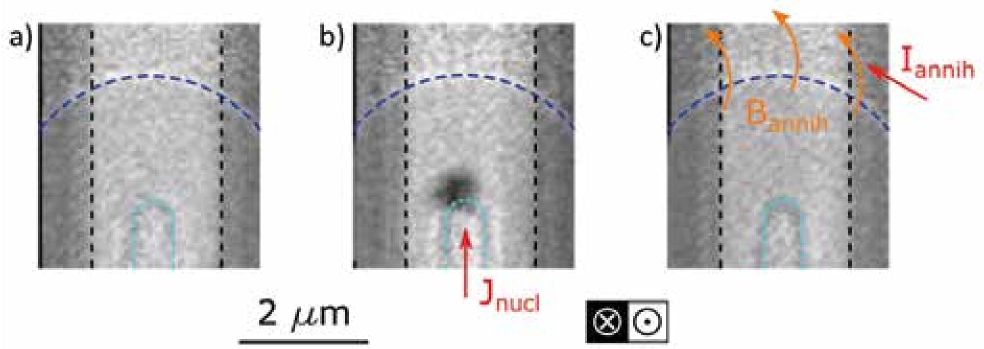


Figure 7: Quasi-static investigation of the skyrmion nucleation and deletion processes. (a–c) Quasi-static XMCD-STXM images of the current-induced nucleation and field-induced deletion of a magnetic skyrmion. (a) Initial uniform magnetic configuration. The edges of the microwire are marked by the black dashed lines, the edge of the injector is marked by the light blue dashed line, and the edge of the microcoil is marked by the dark blue dashed line. (b) Nucleation of a magnetic skyrmion (area of dark contrast in the image) by injecting a 5 ns long current pulse in the microwire. (c) Recovery of the initial magnetic configuration by injecting a current pulse across the microcoil, leading to the generation of an out-of-plane magnetic field pulse. (Figure taken from [33], with permission of the American Chemical Society])

display a low velocity of less than 1 cm·s^{-1}. As mentioned in the previous section, for a realistic device, higher current densities are required to drive skyrmions at speeds of order tens m·s^{-1}.

The often quoted critical requirements for practical applications of skyrmions are i) their stability at room temperature (or even higher), ii) for high-density applications, a compact size of less than 100 nm and ideally closer to 10 nm, iii) for spintronics applications, controllability by weak external stimuli such as low electric currents, magnetic fields or electric fields. Some of the presently known bulk skyrmion host systems at least partially satisfy these conditions, and as such they may eventually find use in applications. Still, these requirements are more readily achieved by skyrmions in synthetic MML systems. A clutch of discoveries in 2016 of mid- to small-sized skyrmions (< 100 nm) at room temperature, in zero magnetic field, and furthermore their current-driven dynamics, was reported in various multilayers such as Pt/CoFeB/MgO [37], Pt/Co/Ta [38] and Pt/Co/MgO [39] stacks. This makes synthetic MMLs presently the most promising class of skyrmion host system for the nascent field skyrmion-based electronics, or skyrmionics.

The field of skyrmionics focuses principally on the development of information storage and processing devices using skyrmions, whereby the energy-efficient writing, deletion, read-out and processing processes are needed. The writing and deleting of skyrmions in various systems has been achieved by different methods, such as by using magnetic fields, electric fields, electric currents, and laser pulses, while the electrical read-out of a skyrmion can be achieved making use of the topological Hall effect or an embedded magnetic tunnel junction (MTJ) that detects a skyrmion-induced change in the magnetoresistance. For further details of the research status on these issues, the reader is referred to one of the reviews cited at the end of the article.

The most highlighted application concept is that of skyrmion racetrack memory device initially proposed by Fert *et al.* in 2013 [40] as development of the domain-wall based racetrack memory concept proposed earlier by Parkin *et al.* in 2008 [41]. In the context of multilayer systems, many theoretical studies have elucidated the current-induced dynamics of transporting isolated skyrmions along otherwise ferromagnetic racetracks, though the experimental realization of a fully functional skyrmion-based racetrack memory device is still awaiting demonstration. By means of a conceptual example of a racetrack memory concept, Figure 8 shows a hypothetical material in which both skyrmions and antiskyrmions may exist (presumably as metastable states) and information is encoded in terms of their different in-plane magnetization textures.

Bulk ferrimagnetic materials play a central role in microwave technology already for oscillators, band-pass filters, power limiters, and circulators. As their operational frequencies are tunable via an applied magnetic field they are exploited over a large frequency regime from roughly 1 to 100 GHz. In this regime the free-space wavelength of electromagnetic waves varies from about 30 cm to 3 mm, respectively. Key microwave components such as circulators are (still) of a similar macroscopic size to directly modify the microwave signal transmission via their non-resonantly excited dynamic magnetic permeability. Future mobile communication and the internet of things however require miniaturized and multi-functional microwave devices. Here skyrmion crystals if realized in potentially low-damping thin-film materials might put a new spin on microwave technologies based on magnets. Their periodic lattice can be viewed as an artificial crystal for collective spin excitations, i.e., spin waves (magnons) [42]. It offers a specifically tailored band structure for magnons which can be controlled e.g. by a magnetic or, more efficiently, by an electric field in case of magnetoelectric coupling. Fine-tuning J and D magnonic crystals with lattice constants on

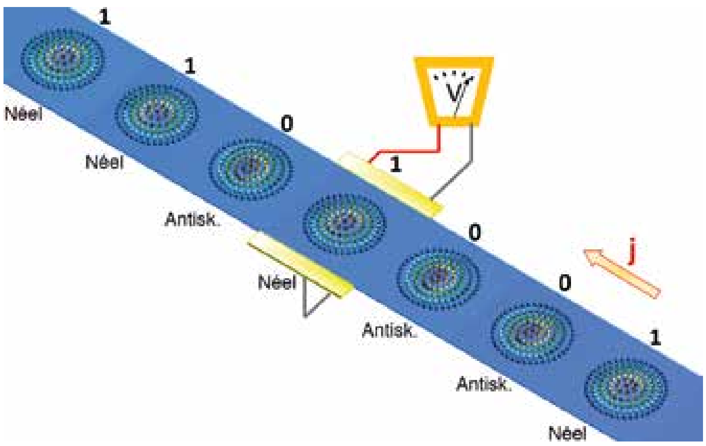


Figure 8: Racetrack memory concept based on a train of skyrmions and antiskyrmions. Here Néel-type skyrmion and antiskyrmion represent either a digital 1 or 0, respectively. Required information can be transported based on the manipulation of the skyrmion-antiskyrmion train through pulses of applied current density j. The detection scheme is able to differentiate between the in-plane magnetization textures as they pass through the region with gold voltage contacts. In the present case, the skyrmions and antiskyrmions can be distinguished by producing a different sign of THE as determined in transport measurements.

the 10 nm length scale can be envisioned which are much smaller than ever achieved by state-of-the-art top-down nanotechnology in clean rooms. Microwave signals coupled to the corresponding magnons in the GHz frequency regime experience wavelengths which would be five to six orders of magnitude shorter than their corresponding free-space wavelength. Skyrmion crystals could thereby serve as nanoscale on-chip band-pass filters which process microwave signals on unprecedentedly short length scales, further fueling the prospects of magnonics.

Other application concepts that involve harnessing the GHz energy excitations of the skyrmion internal modes thus include skyrmion-based microwave detectors [43] and nano-oscillator applications [44], the creation and exploitation of skyrmion-based logic computing gates [45] and transistor devices [46], each of which can be combined with a racetrack architecture, and even biophysics-inspired devices such as an artificial synapse device for neuromorphic-like computing systems [47]. Overall, it is anticipated that skyrmion-based electronic devices will emerge eventually to achieve a widespread commercial and societal impact.

More skyrmions in the future?

As illustrated, magnetic skyrmions have inspired studies from fundamental physics to possible applications. With this article we sought to provide appetizers by highlighting a few of these exciting developments, chosen in part with a bias to Swiss activities in the field. For readers who would like to learn more, we recommend some of the recent reviews [48-52]. Whether skyrmions will eventually become part of future main-stream technologies remain to be seen, but the study of their rich physics has already led to new ways of thinking about topological magnetic textures, their manipulation and potential uses. Many more exciting results and extensions to the field continue to appear from a growing scientific community.

Acknowledgments

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References

[1] G. E. Brown (ed.). Selected Papers, with Commentary, of Tony Hilton Royle Skyrme. World Scientific, Singapore, 1994.
[2] A. N. Bogdanov and D. A. Yablonskii, Sov. Phys. JETP **68**, 101 (1989).
[3] A. Bogdanov and A. Hubert, J. Magn. Magn. Mater. **138**, 255 (1994).
[4] U. K. Rössler, A. N. Bogdanov, C. Pfleiderer, Nature **442**, 797 (2006).
[5] B. Binz, A. Vishwanath, V. Aji, Phys. Rev. Lett. **96**, 207202 (2006).
[6] S. Muhlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii and P. Boni, Science **323** 915 (2009)
[7] X. Z. Yu, Y. Onose, N. Kanazawa, J. H. Park, J. H. Han, Y. Matsui, N. Nagaosa and Y. Tokura, Nature **465**, 901 (2010)
[8] S. Seki, X. Z. Yu, S. Ishiwata and Y. Tokura, Science **336**, 198 (2012)
[9] T. Tokunaga, X. Z. Yu, J. S. White, H. M. Rønnow, D. Morikawa, Y. Taguchi, Y. Tokura, Nat. Commun. **6**, 7638 (2015)
[10] K. Karube, J. S. White, N. Reynolds, J. L. Gavilano, H. Oike, A. Kikkawa, F. Kagawa, Y. Tokunaga, H. M. Rønnow, Y. Tokura, Y. Taguchi, Nat. Mater. **15**, 1237 (2016)
[11] K. Karube, J. S. White, D. Morikawa, M. Bartkowiak, A. Kikkawa, Y. Tokunaga, T. Arima, H. M. Rønnow, Y. Tokura and Y. Taguchi, Phys. Rev. Materials **1**, 077405 (2017)
[12] I. Kezsmarki, S. Bordacs, P. Milde, E. Neuber, L. M. Eng, J. S. White, H. M. Rønnow, C. D. Dewhurst, M. Mochizuki, K. Yanai, H. Nakamura, D. Ehlers, V. Tsurkan and A. Loidl, Nat. Mater. **14**, 1116 (2015)
[13] A. K. Nayak, V. Kumar, T. Ma, P. Werner, E. Pippel, R. Sahoo, F. Damay, U. K. Rossler, C. Felser and S. S. P. Parkin, Nature **548**, 561 (2017)
[14] *https://en.wikipedia.org/wiki/2019_redefinition_of_the_SI_base_units*
[15] Naoto Nagaosa & Yoshinori Tokura, Nature Nanotechnology volume **8**, 899 (2013)
[16] J. Raabe *et al.*, Review of scientific instruments **79**, 113704 (2008)
[17] P. Huang *et al.*, arxiv:1807.08352
[18] J. Rajeswari *et al.*, PNAS **112**, 14212 (2015)
[19] F. Jonietz, S. Mühlbauer, C. Pfleiderer, A. Neubauer, W. Münzer, A. Bauer, T. Adams, R. Georgii, P. Böni, R. A. Duine, K. Everschor, M. Garst and A. Rosch, Science **330**, 1648 (2010).
[20] J. Zang, M. Mostovoy, J. H. Han and N. Nagaosa, Phys Rev Lett **107**, 136804 (2011)
[21] J. Iwasaki, M. Mochizuki and N. Nagaosa, Nat. Commun. **4**, 1463 (2013).
[22] Takuro Sato, Wataru Koshibae, Akiko Kikkawa, Tomoyuki Yokouchi, Hiroshi Oike, Yasujiro Taguchi, Naoto Nagaosa, Yoshinori Tokura and Fumitaka Kagawa, Phys. Rev. B **100**, 094410 (2019)
[23] D. Okuyama, M. Bleuel, J. S. White, Q. Ye, J. Krzywon, G. Nagy, Z. Q. Im, I. Živković, M. Bartkowiak, H. M. Rønnow, S. Hoshino, J. Iwasaki, N. Nagaosa, A. Kikkawa, Y. Taguchi, Y. Tokura, D. Higashi, J. D. Reim, Y. Nambu & T. J. Sato, Communications Physics **2**, 79 (2019)
[24] Junichi Iwasaki, Masahito Mochizuki & Naoto Nagaosa, Nature Nanotechnology **8**, 742 (2013)
[25] X. Zhang *et al.*, arXiv:1906.04718
[26] P. Huang *et al.*, Nano Lett. **18** 5167 (2018)
[27] G. Berruto *et al.*, PRL **120** 117201 (2018)
[28] M. Mochizuki, Phys. Rev. Lett. **108**, 017601 (2012)
[29] Y. Onose, Y. Okamura, S. Seki, S. Ishiwata and Y. Tokura, Phys. Rev. Lett. 109, 037603 (2013)
[30] T. Schwarze, J. Waizner, M. Garst, A. Bauer, I. Stasinopoulos, H. Berger, C. Pfleiderer and D. Grundler, Nature Mater **14** 478 (2015)
[31] C. Moreau-Luchaire et al., Nature Nanotechnology **11**, 444 (2016).
[32] A. Belabbes, G. Bihlmayer, F. Bechstedt, S. Blügel and A. Manchon, Phys. Rev. Lett. **117**, 247202 (2016)
[33] S. Finizio, K. Zeissler, S. Wintz, S. Mayr, T. Weßels, A. J. Huxtable, G. Burnell, C. H. Marrows and J. Raabe, Nano Letters **19**, 7246 (2019).
[34] S. Woo *et al.*, Nat Commun **9**, 959 (2018).
[35] K. Zeissler *et al.*, Nature Nanotechnology **13**, 1161 (2018).
[36] T. Schultz, R. Ritz, A. Bauer, M. Halder, M. Wagner, C. Franz, C. Pfleiderer, K. Everschor, M. Garst, A. Rosch, Nat. Phys. **8**, 301 (2012)
[37] S. Woo *et al.*, Nat. Mater. **15**, 501–506 (2016)
[38] O. Boulle *et al.*, Nat. Nanotechnol. **11**, 449–455 (2016)
[39] W. Jiang *et al.*, AIP Advances **6**, 055602 (2016).
[40] A. Fert, V. Cros, J. Sampaio, Nat. Nanotech. **8** 152, 2013
[41] S. S. P. Parkin, M. Hayashi and L. Thomas, Science **320**, 190 (2008)
[42] M. Garst, J. Waizner and D. Grundler, J. Phys. D: Appl. Phys. **50**, 293002 (2017)
[43] G. Finocchio, M. Ricci, R. Tomasello, A. Giordano, M. Lanuzza, V. Puliafito, P. Burrascano, B. Azzerboni and M. Carpentieri, Appl. Phys. Lett. **107**, 262401 (2015)
[44] S. F. Zhang, J. B. Wang, Q. Zheng, Q. Y. Zhu, X. Y. Liu, S. J. Chen, C. D. Jin, Q. F. Liu, C. L. Jia and D. S. Xue, New J. Phys. **17**, 023061 (2015)
[45] X. Zhang, M. Ezawa and Y. Zhou, Sci. Rep. **5**, 9400 (2015)
[46] X. Zhang, Y. Zhou, M. Ezawa, G. P. Zhao and W. Zhao, Sci. Rep. **5**, 11369 (2015)
[47] Y. Huang, W. Kang, X. Zhang, Y. Zhou and W. Zhao, Nanotechnology **28**, 08LT02 (2017)
[48] Albert Fert, Nicolas Reyren, Vincent Cros, Nature Reviews Materials **2**, 17031 (2017)
[49] K. Everschor-Sitte *et al.*, Journal of Applied Physics **124**, 240901 (2018)
[50] Yan Zhou, National Science Review, **6**, 210 (2019)
[51] Giovanni Finocchio *et al.*, Journal of Physics D: Applied Physics, **49**, 423001 (2016)
[52] Wanjun Jiang *et al.*, Physics Reports, **704**, 1 (2017)

Celebrating George E. Lemaître's 125th anniversary

A report about the fall symposium of the SPS

Claus Beisbart, Uni Bern

125 years ago, in 1894, the Belgian physicist and astronomer Georges Edouard Lemaître was born. Lemaître made lasting contributions to relativistic cosmology. It is no coincidence that the most significant class of cosmological models is named after him (and A. Friedmann, H. P. Roberson and G. Walker). In fact, Lemaître suggested that the Universe goes back to a primeval atom – now called the Big Bang.

The SPS took Lemaître's 125th birthday as an opportunity to honor his scientific work with a symposium organized jointly with the SCNAT. The event took place in the Kuppelsaal in the main building of the University of Bern and attracted a large audience of about 70 people. It was part of a series of colloquia that feature important figures from the history of physics; the previous symposium from this series had focused on Richard Feynman.

The first speaker was Prof. Harry Nussbaumer from the ETH Zürich. The main task of his talk was to contextualize Lemaître's work in the astronomy of his time. As Nussbaumer pointed out, during the 1920ies, it was still debated whether the so-called nebulae were island universes (galaxies) of their own. Cosmology was thus still quite speculative, only few people working on it, among them Aleksandar Friedmann, a Russian mathematician who obtained the first non-static solutions to Einstein's field equations. In a paper of 1927, Lemaître proposed a homogeneous and isotropic dynamic, expanding model of the Universe that starts with an extremely hot and dense state. He realized that his model predicts galaxies to have a redshift that is roughly proportional to their distance. This paper was at the center of the second talk by Prof. Jean-Pierre Luminet from the Laboratoire d'Astrophysique de Marseille. He stressed that the paper did not become widely known because it was published in French. Thus, Edwin Hubble did not refer to it when he discovered in his data linear relationship between the distances and redshifts of galaxies in 1929. For a long time, this relationship was known as *Hubble's Law*, but in 2018, the International Astronomical Union recommended to rename it *Hubble-Lemaître Law*. The third speaker, Prof. Norbert Straumann from the University of Zürich, turned to a later contribution by Lemaître. In 1933, the Belgian physicist provided an inhomogeneous, but isotropic solution to Einstein's equation. Straumann pointed out that this model has recently seen a revival: It was used to provide an alternative to the hypothesis that so-called dark energy leads to an accelerated expansion.

The symposium finished with an evening lecture presented by Prof. Friedrich Thielemann from the University of Basel. He turned to the origin of the various elements and thus made a connection with another jubilee in 2019: 150 years ago, Mendeleev first presented a table that is now taken to be the decisive forerunner of the periodic system of chemical elements. This discovery is intimately linked with Lemaître's work, because the nuclei of the light elements originated shortly after the Big Bang during what is now called Big Bang Nucleosynthesis. The nuclei of the heavier elements were produced later, in particular from nuclear reactions within stars. All in all, the fascinating talks made vivid how important Lemaître's contributions are for contemporary physics. They also showed the modesty and generosity of Lemaître who did not hesitate to acknowledge the contributions of other physicists.

From left to right: Friedrich Karl Thielemann, Hans Peter Beck (SPS President), Harry Nussbaumer, Jean-Pierre Luminet, Norbert Straumann, Claus Beisbart (Symposium Organiser). Image: SCNAT

The slides of all four talks are available on https://www.sps.ch/events/diverse-veranstaltungen/125th-anniversary-of-georges-lemaitre/ . In addition, we are very glad to publish a written version of Prof. Straumann's talk on the next pages.

The Belgian Physical Society organised a symposium this year on 23 May, in collaboration with EPS and the sister universities KU Leuven and the Université Catholique de Louvain, to honour Georges Edouard Lemaître. In the afternoon the EPS Historic Site Plaquette was unveiled at the wall of the Heilige Geest College in Leuven (Naamsestraat 40) where Lemaître wrote his famous Nature paper in 1931 on the "primordial atom". https://www.belgianphysicalsociety.be/page/34

History and Philosophy of Physics (26)

On Lemaître's inhomogeneous cosmological model of 1933 and its recent revival

Norbert Straumann, Physik-Institut, University of Zürich

1 Introduction

The previous two talks at this symposium by Harry Nussbaumer and Jean-Pierre Luminet have clearly shown the crucial role of Georges Lemaître in the development of what we now call the standard model of cosmology. Already in 1933 he developed a more general model by relaxing the high symmetries of the Friedmann-Lemaître (FL) models, which are spatially homogeneous and isotropic. His extended model is inhomogeneous, but he kept the isotropy. Otherwise things would have become at the time hopelessly difficult. Only now – with the power of computer systems – it has become possible to study the evolution of inhomogeneous and anisotropic models in the framework of GR.

Lemaître's inhomogeneous model experienced an astonishing revival after 2000 when observations convincingly showed that the expansion of the universe is accelerating since about 2 billion years ($z \simeq 0.6$). This fact was almost universally attributed to the presence of a mysterious form of so-called *dark energy*, for instance a positive cosmological constant (still compatible with all observations).

Since the required *magnitude* of dark energy is a mystery, a minority of cosmologists has afterwards investigated the possibility that the observational findings might be caused by inhomogeneities in the distribution of matter and other quantities. More concretely, it was suggested that we live in an underdense region of the universe centered not far from us, and do not need dark energy.

I thought it would be fitting for this meeting on the occasion of Lemaître's 125th birthday to present his inhomogeneous model and to summarize its recent applications in cosmology ([1], English translation [2]).

2 Lemaître shows that the "Schwarzschild singularity" is apparent

I begin with a late Sect. 11 of this paper, which deviates from the central theme, entitled: **SCHWARZSCHILD'S EXTERIOR FIELD.** Almost all researchers in the field have overlooked this most remarkable contribution. (I learned about it only quite recently.)

Lemaître shows in this section that the so-called Schwarzschild singularity, that disturbed relativists over decades, is spurious. In his own words:

> "***The singularity of the Schwarzschild field is thus a fictitious singularity***" ([2], p. 676, emphasis added).

He showed this by transforming the standard form of the metric to new coordinates which are defined by a congruence of freely falling test particles in radial directions, starting at rest infinitely far away (radial parabolic motion) [1]. If Lemaître's insight would have been generally appreciated, the history of black hole physics would have been different, because the apparently singular Schwarzschild surface would probably soon have been understood as an event horizon [8].

[1] In 1963 Novikov introduced coordinates adapted to a congruence of non-parabolic initial conditions. Their relation to the standard Schwarzschild coordintes is much more complicated.

3 Qualitative description of Lemaître's inhomogeneous model

What Lemaître mainly does in the paper is to derive from Einstein's field equations the basic equations describing the time-dependent behavior of a spherically symmetric dust of stars or related models of the universe (see Fig. 1). For a long time his work was known under the name "Tolman model" (sometimes "Tolman-Bondi" model). This is strange since Tolman made no secret of the fact that the work was Lemaître's and quoted Lemaître. However, Bondi did not cite Lemaître. I could refer to papers, for instance in the *Astrophysical Journal* as late as 1995 by well-known authors, who used the "Tolman-Bondi" model for testing a new code. J. Peebles was one of the few who always cited the works by Lemaître in his books on cosmology. Most authors now use the term "Lemaître-Tolman-Bondi (LTB) model".

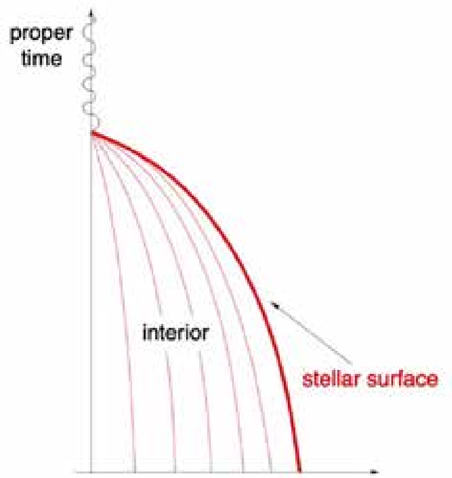


Figure 1: Worldlines of dust shells in spherical collapse. They all reach the singularity at the same proper time.

The famous work by J. Robert Oppenheimer and his student Hartland Snyder in 1939 on the gravitational collapse of a simplified stellar model [9] is a special application of Lemaître's equations, which they did not know. In their paper they describe crucial aspects of the collapse to a black hole, but because of the apparent Schwarzschild singularity a full understanding came only many years later. For the problem of a smooth matching of the internal and the external metric of the collapsing star, the new regularising coordinates of Lemaître for the Schwarzschild geometry would also have been significant.

The straightforward extension of Lemaître's treatment of the problem to ideal fluids with non-vanishing pressure was developed in an important paper by Misner and Sharp in 1964 [10]. Their equations became an essential part for numerical simulations of spherically symmetric collapse calculations and supernova explosions in the 1980s. More realistic collapse calculations, not assuming spherical symmetry, became possible with the impressive developments of numerical relativity and by a continued increase of computer power. This has become a vast field.

The technical description of the LTB model is postponed (s. Appendix), and we turn to observational tests.

4 Recent confrontation with observations and results of the LTB model

The observations of luminosities of supernovae of type Ia shortly before 2000 were almost universally interpreted as the result of an accelerated expansion of the universe, caused by *dark energy* (for instance a positive cosmological constant). Additional independent observations, in particular the measurements of the anisotropies in the cosmic microwave background and galaxy surveys, supported this interpretation with increasing accuracy.

Since the required *magnitude* of dark energy is a mystery, a minority of cosmologists in recent years has investigated the possibility that the observational findings might be caused by inhomogeneities in the distribution of matter and other quantities. More concretely, it was suggested that we live in an under-dense region of the universe centered not far from us, and do not need dark energy. Since the cosmic microwave background is highly isotropic, it is reasonable to start with simplified spherically symmetric but *inhomogeneous* models. For this reason, the LTB model was revived. (This can be regarded as an example for nonlinear deviations of FL-models. With the tools of numerical relativity more general studies are possible.)

The model is determined by the matter density $\rho(t_0,r)$ at the present time (apart from a few cosmological parameters) that is constrained by observational data. In what follows I concentrate on the detailed analysis in [11] (that contains references to related work). The authors assume that the early Universe was homogeneous until the time of recombination and followed standard physics, including decoupling. They use the measured local Hubble rate $H_0 \simeq 74$ km s^{-1} Mpc^{-1}, the supernovae data and the angular diameter distance to the surface of last scattering, $D_A = 12.80 \pm 0.068$ Mpc from the *Planck* data. For the latter they follow a method for analyzing the CMB anisotropies in a manner that is as independent as possible of late-time cosmology [13], without using perturbation theory on an LTB background (we postpone explanations on this important fact). The following main conclusions result:

(i) The local Hubble rate and supernovae data can easily be fitted (for $\Lambda = 0$); the data favor the formation of large and deep voids (see Fig. 2).

(ii) "Model-independent" constraints from *Planck* + supernovae data imply an ***unrealistically low value of the local Hubble rate***, $H_0 \approx 39$ km s^{-1} Mpc^{-1}.

As [11], p. 8, put it, "*LTB models with a constant bang time function and zero cosmological constant are inconsistent with current data*" (emphasis added).

After this, the final sections of [11] are devoted to LTB models with a non-vanishing cosmological constant. It should be recalled that based on the famous Lovelock theorem any

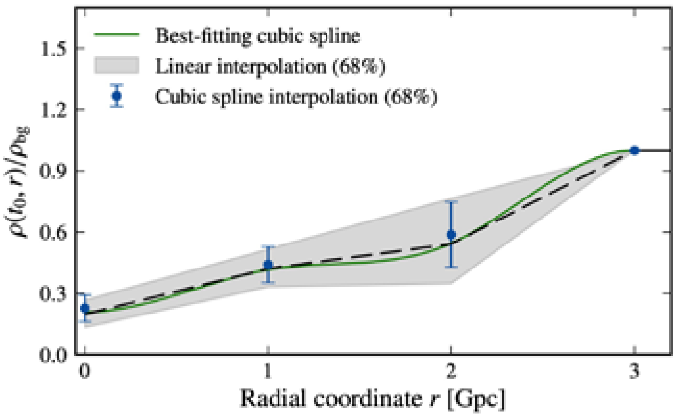


Figure 2: Deviations of $\rho(t_0, r)$ from spacial homogeneity for $r < 3$ Gpc for $\Lambda = 0$. The models were forced to converge to the background density at $r = 3$ Gpc (Fig. 3 from [11]).

metric theory of gravity has, without convincing counterarguments, at least two coupling constants: Newton's constant G and the cosmological constant. This was also Lemaître's view. He repeated this very clearly in his contribution to the famous Schilpp volume "Albert Einstein: Philosopher - Scientist" [16], entitled: *The Cosmological Constant*. I quote from Section 1:

> *Even if the introduction of the cosmological constant "has its sole original justification, that of leading to a natural solution of the cosmological problem" (Einstein), it remains true that Einstein has shown that the structure of his equations quite naturally allows for the presence of a second constant beside the gravitational one. This raises a problem and opens possibilities which deserve careful discussion. The history of science provides many instances of discoveries which have been made for reasons which are no longer considered satisfactory. It may be that the discovery of the cosmological constant is such a case.*

This is what cosmological data told us.

The authors of [11] arrived with their detailed analysis at the result that the data is, of course, better fitted under the LTB model than under the FL model (with Λ), but that the improvement is "almost negligible". So *current data show that LTB models on Gpc-scales must be close to FL models with* $\Lambda \neq 0$ (see Fig. 3).

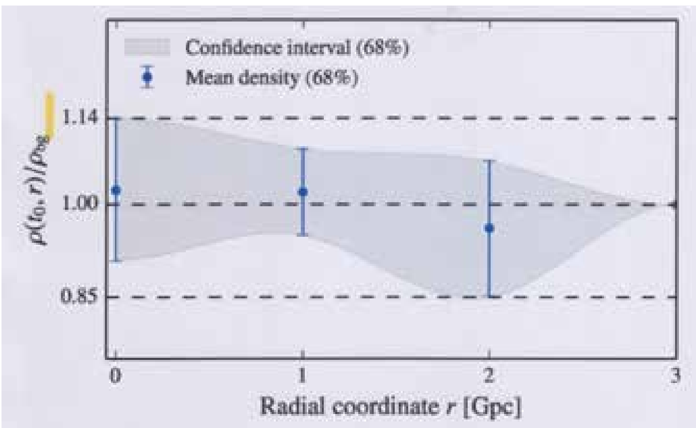


Figure 3: Deviations of $\rho(t_0, r)$ from spacial homogeneity for $r < 3$ Gpc for $\Lambda \neq 0$. The models were forced to converge to the background density at $r = 3$ Gpc (Fig. 10 from [11]).

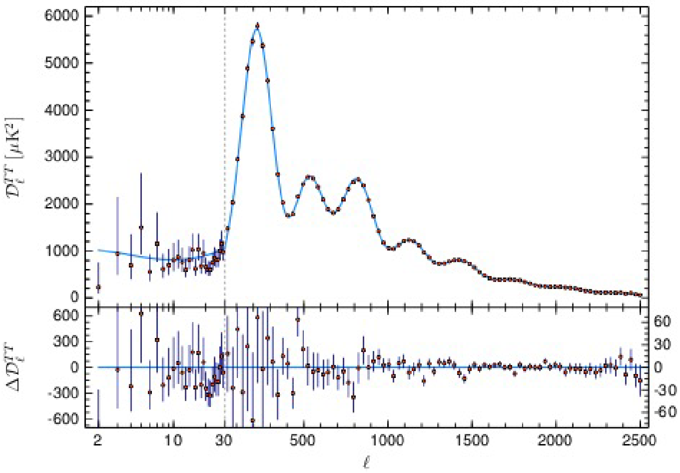


Figure 4: Planck temperature power spectrum as measured by the Plack satellite and fit of an FL model. Figure 1 from [12].

Their analysis of the *Planck* data (Fig. 4) is, as they admit, limited since linear perturbation theory for an LTB background is very complicated and still not sufficiently developed. Because this background has less symmetries than a FL background, gauge-invariant perturbations in a spherical harmonic decomposition are coupled by systems of linear *partial* differential equations, and not by hierarchies of *ordinary* differential equations as for the simpler FL models. (This is familiar from other fields of physics.) For existing attempts we refer to [17].

Without such analysis certain parameters are, however, well determined by the data. We illustrate this for the angular diameter distance D_A to the last scattering surface. This can be obtained from the CMB observations, with little dependence on the cosmic evolution from this surface to the present, in particular if inhomogeneities affect the evolution. Qualitatively, this can be understood as follows.

The formation of the radiation fluctuations – the primordial spectra – are in our standard model very well understood and worked out with high precision. While the observed spectra, for instance the temperature-temperature correlation in Fig. 3, are influenced by the later evolution, the sequence of peaks and troughs reflects a characteristic scale on the surface of the last scattering. A priori, it is, however, possible that we see a scale that was originally formed during the early universe by standard cosmology, but was afterward changed in an unknown manner by post-recombination evolution.

Physically, the characteristic scale imprinted on the last scattering surface (LSS) is the so-called *sound horizon* at decoupling, which is the distance sound waves in the photon-baryon plasma can travel from early times until they reach this surface. Vonlanten, Räsänen & Durrer [13], and a later extension by Audren [14] using the *Planck* results, showed that the late-time cosmology preserves this scale for short distance fluctuations. More precisely, they demonstrated that the part of the spectrum with l larger than about 40 is predominantly rigidly shifted ($l \to S^{-1}l$) and its height is re-scaled. Indeed, it turned out that with such a shift an excellent fit to the observed power spectra is achieved. The resulting scale parameter S determines directly the angular distance D_A to the last scattering surface: $D_A = 12.8^{+0.071}_{-0.065}$ Mpc. (For technical details, I refer to the cited papers.)

It may help to illustrate this for the class of FL models with its various cosmological parameters. The power spectra at the time of recombination do not depend on the parameters Ω_K and Ω_Λ, since they play no role in the evolution until that time. They modify, however, the post-recombination spectra. It turns out that the present power spectra for sufficiently large l values ($l \gtrsim 30$) do not fix their values individually, but a certain function of them, the so-called shift parameter R. This is closely related to S and the angular diameter distance D_A. So this distance is determined by the power spectrum at short distances. It is this aspect that is generalized in a model-independent way in the cited papers [13], [14]. Briefly, the observed power spectrum for ($l \gtrsim 30$) can be fitted by treating D_A as a free parameter, whose physical origin is left open. We have seen that for the LTB model it provides an important restriction of the initial density distribution.

I add to this discussion the following remark on local and global values of the Hubble parameter. In the framework of the FL models it was possible to deduce a precise value for this parameter from fits to the *Planck* power spectra of the cosmic background radiation: $H_0 = 67.8 \pm 0.9$ km s^{-1} Mpc^{-1}. This disagrees with the local value 74 (in the same units) that was obtained earlier by astronomers. This 3.6σ discrepancy caused in recent years lots of discussions and speculations. Last summer a new value for the local H_0 was published by W. Friedman and collaborators, based on a new independent method (using the tip of the red giant branch). With this, the situation is now confusing, since the new value lies almost exactly in the middle between the previous two: $H_0 = 69.8 \pm 0.8$ km s^{-1} Mpc^{-1}. This value agrees with the global *Planck* value at the 1.2σ level, and is 1.75σ below the previous local one. For a recent summary of the current measurements of H_0, using various methods including gravitational lensing, see [18].

Planned future observations will hopefully decide whether a discrepancy remains for the FL cosmology. Recent cosmological general relativistic simulations [19] strongly indicate that a 3.6σ discrepancy cannot be explained with inhomogeneities.

Appendix. Basic equations of the LTB model

For readers familiar with the essentials of General Relativity we present in this final section the basic equations of the LTB model. For a spherically symmetric dust model about a distinct central worldline the metric has in suitable coordinates (t, r, ϑ, φ) the form (see [15], Sect. 4.10.1)

$$g = -dt^2 + e^{2b(t,r)}dr^2 + R^2(t,r)(d\vartheta^2 + \sin^2\vartheta d\varphi^2). \quad (1)$$

Einstein's field equations imply that

$$e^{2b(t,r)} = \frac{(R'(t,r))^2}{1-k(r)}, \quad (2)$$

where $k(r)$ is a function of r alone, for which the boundary condition $k(0) = 0$ can be imposed. (In what follows a prime denotes the partial derivative with respect to r and a dot the time derivative.) Another arbitrary function is a kind of mass function, $M(r)$, defined by

$$M'(r) = 4\pi R^2(t,r)\,R'(t,r)\,\rho(t,r),\;\; M(0) = 0, \qquad (3)$$

where $\rho(t, r)$ is the matter density (of dust, for instance dark matter). Einstein's field equations imply that M is time independent.

The dynamical field $R(t, r)$ of the metric satisfies the "Hamiltonian constraint" equation

$$\frac{\dot{R}^2}{R^2} = \frac{2GM(r)}{R^3} + \frac{8\pi G}{3}\rho_\Lambda - \frac{k(r)}{R^2}, \qquad (4)$$

which is a differential equation for $R(t, r)$ as a function of t with r as a parameter. On the right we have included, following Lemaître, the contribution of the Λ term ($\rho_\Lambda = \Lambda/8\pi G$).

The basic dynamical equation (4) generalizes the Friedmann equation. For the discussion of these basic equations we introduce several derived functions:
$H(t, r)$ denotes the local Hubble rate

$$H(t,r) := \frac{\dot{R}(t,r)}{R(t,r)}, \qquad (5)$$

and $H_0(r)$ its value at the present time t_0

$$H_0(r) := H(t_0, r). \qquad (6)$$

We define local density parameters $\Omega_M(r)$, $\Omega_\Lambda(r)$, $\Omega_K(r)$ by

$$2GM(r) =: H_0^2(r)\,\Omega_M(r)\,R_0^3(r),\; \Omega_\Lambda(r) := 8\pi G\frac{\rho_\Lambda}{H_0^2(r)},\; \Omega_K := 1 - \Omega_M - \Omega_\Lambda, \qquad (7)$$

where $R_0(r) := R(t_0, r)$. With these definitions we can rewrite the Hamiltonian constraint (6) as

$$H^2 = H_0^2\left[\Omega_M\left(\frac{R_0}{R}\right)^3 + \Omega_\Lambda + \Omega_K\left(\frac{R_0}{R}\right)^2\right]. \qquad (8)$$

The local spatial curvature $k(r)$ is given by

$$k(r) = -H_0^2\Omega_K R_0^2 = 1 + H_0^2(1 - \Omega_M - \Omega_\Lambda)\,R_0^2(r). \qquad (9)$$

Equation (8) looks like the well-known equation in Friedmann-Lemaître (FL) models [2]

$$H^2 = H_0^2\left[\Omega_M\left(\frac{a_0}{a}\right)^3 + \Omega_\Lambda + \Omega_K\left(\frac{a_0}{a}\right)^2\right], \qquad (10)$$

where $a(t)$ is the scale factor, but with r-dependent functions $H_0(r)$, $\Omega_M(r)$, etc. Lemaître did a lot of analytic work based on these equations, but solutions can be obtained only for idealized problems. This part is no longer really interesting, since we now have the help of computers. For instance, for the luminosity-redshift relation, one must solve a pair of nonlinear differential equations.

Since the radial coordinate r is arbitrary, one can eliminate one arbitrary function. For instance, by choosing the gauge $R(t_0, r) = r$, the mass function $M(r)$ is according to (5) determined by the density profile $\rho(t_0, r)$ at the present time t_0:

$$M(r) = 4\pi G\int_0^r \rho(t_0, r')\,r'^2\,dr'. \qquad (11)$$

From (11) we obtain for the present time

$$t_0 = \frac{1}{H_0(r)}\int_0^1 \frac{dx}{\sqrt{\Omega_M(r)\,x^{-1} + \Omega_\Lambda(r)\,x^2 + \Omega_K(r)}}. \qquad (12)$$

Here we left out a possible additive r-dependent term (the so-called bang time function), assuming that the Big Bang occurs synchronously, as in FL models. (This should, in any case, be much smaller than t_0.) Because we want to match the solution to a homogeneous FL solution in the outer space, t_0 is chosen to be equal to the FL value (for the best fit). With all this the previous equations *determine all quantities of interest by* $\rho(t_0, r)$ plus the Hubble constant and the cosmological constant.

2 For these $R(t, r) = a(t)r$.

References

[1] G. Lemaître, Annales de la Société Scientifique de Bruxelles, **53**, 51 (1933).
[2] G. Lemaître, General Relativity and Gravitation, Vol. 29, No. 5 (1997).
[3] R. C. Tolman, Proc. Nat. Acad. Sci. **20**, 169 (1934)
[4] H. Bondi, MNRAS **107**, 410 (1947).
[5] A. Einstein, *Collected Papers*. Vol. 8, Doc. 181.
[6] K. Schwarzschild, in A. Einstein, *Collected Papers*. Vol. 8, Doc. 188.
[7] A. Einstein, Ann. Math. (USA) **40**, 922-936 (1939).
[8] N. Straumann, *SPG Mitteilungen*, Nr. 59, 38 (2019).
[9] J. R. Oppenheimer and H. Snyder, On continued gravitational collapse, Phys. Rev. **56**, 455-459 (1939).
[10] C. W. Misner and D. H. Sharp, Phys. Rev. B **136**, 571 (1964).
[11] M. Redlich, et al., A&A **570**, A63 (2014).
[12] N. Aghanim et al. [Planck Collaboration]. Planck 2018 results. VI. Cosmological parameters, arXiv:1807.06209 [astro-ph.CO].
[13] M. Vonlanten, S. Räsänen, R. Durrer, 2010, J. Cosmol. Astropart. Phys. **8**, 23 (2010); arXiv: 1003.0810.
[14] B. Audren, MNRAS **444**, 827 (2014).
[15] N. Straumann, *General Relativity*, Second Edition, Graduate Texts in Physics, Springer (2013).
[16] G. Lemaître, The Cosmological Constant, In *Albert Einstein: Philosopher - Scientist,* edited by P. A. Schilpp. Illinois: The Library of Living Philosophers.
[17] S. Meyer, M. Bartelmann, J. Cosmol. Astropart. Phys. **12**, 025 (2017); arXiv: 1709.04834.
[18] L. Verde, et al., arXiv: 1907.10625 [astro-ph.CO].
[19] J. Adamek, et al., Phys. Rev. D **100**, 021301 (2019).

Physicists in Industry (10)

Preventing catastrophe with physics

Nature is sometimes unpredictable. Especially in the mountains there can be only seconds that separate disaster from getting away. Our interview partner is physicist Dr. Lorenz Meier, founder and CEO of *Geopraevent AG*, who develops, deploys and operates systems that monitor and alert to make the difference.

Geopraevent is offering complete solutions that include sensor hardware, software and control e.g. of traffic signs and alarms in extreme environments. What is the main challenge in deploying such systems?

There is a number of challenges that need to be solved before a system improves safety on a road or a railway: as a still quite young company with new technology, we need to find customers that are ready for something new. That is not so obvious in an industry that deals with processes (like for example avalanches) that are known and dealt with since hundreds of years. Not every potential customer has the possibility to try new innovations and for employees, for example at local authorities, it can be quite a lot of work to get such a project started. Luckily, we have some excellent references (like for example our avalanche radars in Zermatt that are operational since 2015) and very satisfied customers that are happy to share their experiences and convince others to start a project with us. Once this process starts, there is a lot of details to be discussed before we can actually start working on the system: we need to know where to place sensors, where to install traffic lights or other alerting equipment, how to connect the different parts of the system, what level of redundancy is required etc. We usually work with partner companies like geological consultants that tell us how they assess the risks and what scenarios they expect. This can include avalanche simulations or geological models about how a mountain could fail and where debris can end up. We then build both the system hardware and software, install it, calibrate it and then operate it, i.e. we permanently monitor that the system works as expected. And we offer an online data portal that visualizes the data and allows our clients to interact with their systems, for example by controlling a camera or closing/reopening roads or railways.

What technology is used for monitoring? What are the resolution limits?

We are not limited to just one technology. We try to be a partner for our customers and offer them any technology that is capable of detecting processes relevant for natural hazards. However, we have a focus on advanced radar and image processing. We made a few innovations in these fields during the last years that helped us become the global leader for radar monitoring of natural hazards like snow avalanches, debris flow, landslides or rock fall. The same applies to our image processing systems that take high-resolution images of glaciers or landslide and automatically compute differences in these images. This is a low-cost alternative to radar with some limitations, e.g. during bad weather no measurement is possible with optical methods. Resolution limits depend on a lot of parameters: distance to the target

Avalanche radar with high-resolution camera with autonomous power supply and redundant radio connection for communications at Bear Pass, British Columbia, Canada.

area, field-of-view of the radar or camera used. With radar interferometry, it is possible to detect relative millimeter displacements at several kilometers distance.

What other technologies are likely to become important in the future?

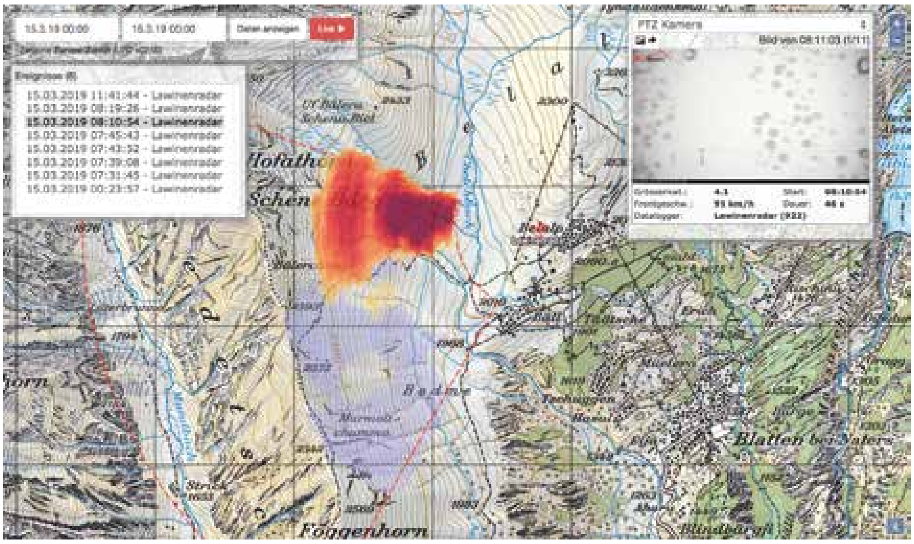
We strongly believe that radar will become even more important in the future and we continue to develop new solutions in this field. I also think that real-time processing of seismic arrays is an interesting approach for monitoring large-scale processes.

How important are algorithms and software?

Smart algorithms are already important and will become even more important in the future. The cost of sensors and hardware as well as energy consumption will continue to decrease while computing power will increase. We will be able to acquire more data at higher resolutions and the need for new algorithms that process such large data sets in real time will increase.

The sensors of your monitoring systems produce a large amount of data. What happens with this data? Is it used for further research purposes?

We use it primarily to improve our algorithms. It's a big asset for us that we have detected already 5000+ avalanches and 2000+ rockfall events. We have tens of TB of radar data stored that we use to test new algorithms with the main goal to keep the probability of detection very high (also for potentially smaller events) while further reducing the false alarm rate. For example, when our radars detect an avalanche high up on a mountain, at what stage do we have to close a road in the valley below? When can the system with very high reliability predict that it will actually hit the road? Currently, we close the road quite early and many events will stop somewhere on the path and not reach a road or railway. If we detect that the event stopped above, we can automatically reopen. But it would certainly be appreciated if we did not close at all for such an event. We also collaborate with geoscience researches in some projects and give them



Data of an avalanche radar plotted in real time on a map.

access to our data so they can investigate things further where we do not have resources.

After the installation, how often it is typically necessary to maintain these systems in their extreme environment?

We try to build our systems in a way that we can remotely fix most issues. Nevertheless, sometimes hardware damage occurs, and somebody needs to fix this on site. As this often requires long travels and expensive helicopter flights, we try to minimize such visits by adding some hardware redundancy to the system. Most of our systems need less than one maintenance visit per year.

Avalanche detected by the same radar in good weather conditions.

You have a PhD in spintronics, for which you were awarded the 2008 SPS Prize for Condensed Matter. When and how did you realize that founding your own company for monitoring natural hazards would be the way to go for you?

After my PhD at IBM Research and ETH Zürich, I worked for Sensirion, which was a great opportunity to learn a lot about how a successful and fast-growing company works and how one deals with customers. It was a great place to work. Nevertheless, I always dreamed about combining my passion for mountains with my interest in science. Therefore, I moved on to the Swiss Institute for Snow and Avalanche Research in Davos. Once there however, I realized that I greatly missed connecting with customers. It is a great feeling if you can solve customer problems and they even pay you money for an interesting project that you loved working on.

Now in hindsight, what were the most difficult challenges and struggles when setting up your company?

The challenges change all the time. While in the beginning the main challenges were to get the technology running reliably and to find first customers, this shifted to how we find new talents, how we organize a company with 20+ employees, how the team works, how we run projects and what processes we need to set up with the goal that everything becomes less dependent on single key persons.

How important or beneficial is it to be based in Zürich, Switzerland?

Zürich has a number of advantages like close connections with ETH, University and the University of Applied Sciences. There's a large talent pool, but there's also strong competition among the different companies trying to get the best people. Salary costs here are twice to three times what they are for example in Italy, were some competitors are based. Office and workshop space is expensive as well and the combination of workshop and office at the same location is not so easy to find in Zürich. We are located at Technopark, which provides great flexibility in the first years of a company but has some limitations for further growth. We not only need more office space, but also workshop and storage areas to build, test and store large systems before exporting them for example to Canada. In general, this puts a lot of pressure on us to be efficient and keep costs under control. The company is profitable since several years, but we have to keep up our efforts to further optimize how we run projects.

Geopraevent AG develops, installs and operates premium monitoring systems for natural hazards like snow or ice avalanches, rock and glacier instabilities, rock fall, floods and debris flows. The company was founded in 2012. It grew at a constant rate and currently employs around 20 employees, mainly software and electronics engineers, physicists and technicians. It currently operates around 100 permanent systems in Switzerland, Austria, France, Norway, Canada, Georgia, Chile and China.

Lorenz Meier studied physics at ETH Zürich and at Lund's University in Sweden from 1997 to 2003. After a year with the Swiss Federal Railways, he completed a PhD in Spintronics at IBM Research and Klaus Ensslin's Nanophysics group in 2007. He then worked for Sensirion AG and the WSL Institute for Snow and Avalanche Research in Davos before founding Geopraevent in 2012.

Kurzmitteilungen - Short Communications

4. Internationales Jost Bürgi Symposium

Das kommende Jost-Bürgi-Symposium findet vom **1. - 2. Mai 2020** im toggenburgischen Lichtensteig im Kanton St. Gallen, dem Geburtsort Bürgis, statt. Es soll wiederum an die Person und das Werk dieses Renaissance-Genies (1552 - 1632) erinnern, dessen Zusammenarbeit um 1600 in Prag mit Johannes Kepler und Tycho Brahe die Astronomie revolutionierte. In seiner Person vereinigte sich der Uhrmacher und Handwerker mit dem Erfinder, Mathematiker, Astronom und dem Künstler.

Jost Bürgi Workshop und Lectures

Das Freitagsprogramm wird diesmal zweigeteilt: während am Vormittag ein **Workshop** für die wachsende Anzahl von Bürgi Interessierten mit der Möglichkeit der Präsentation von Vorträgen organisiert wird, bringt der Nachmittag unter dem Titel **Jost Bürgi Lectures** die Referate eingeladener Wissenschaftshistoriker aus Kassel, Berlin, Prag und Genf. Bereits bestätigt sind für den Workshop zwei Referate von Experten aus USA über die Entstehung (K. Trümper), aber auch die didaktische Vermittlung (K. Clark) der *Bürgischen Logarithmen*, sowie über die deutsche Übersetzung des Hauptwerkes von Copernicus für Jost Bürgi (J. Hamel).
Das Nachmittagsprogramm bringt neue Erkenntnisse über ein *Triangularinstrument* Bürgis (K. Gaulke) und Betrachtungen zur *Geschichte der Ortsbestimmung auf See* (G. Oestmann), die zur damaligen Zeit dank verbesserter astronomischer Vermessungsgeräte genauer und verlässlicher wurde. Bei der Einladung von Referenten aus Kassel und Prag spielt auch die Absicht mit, den Informationsaustausch zwischen Historikern aus beiden Orten, an denen Bürgi seine wichtigsten Jahre verbrachte, mit Lichtensteig zu intensivieren. In diese Zeitperiode passt auch der Genfer *Michel Varro* (1542-1586), dessen Betrachtungen über bewegte Körper bereits die später von Galileo formulierten Gesetzmässigkeiten erkennen lassen. Darüber wird Jan Lacki, der langjährige Leiter der SPG Sektion *Geschichte der Physik* berichten.

Lichtensteig - innovativ seit 1552

Das Samstagsprogramm, das bislang eine Mischung aus Vorträgen über Bürgis Arbeiten, aber auch über seine Auswirkungen in die heutige Zeit brachte (z.B. 2019: Von Bürgis Uhren zu Atomuhren) wird auf Anregung von Stadtpräsident Mathias Müller ebenfalls neu gestaltet. Unter dem Namen **Jost Bürgi Zukunftsforum** und dem Motto *Neudenken, Querdenken, Umdenken* sollen zu Fragen, die uns heute beschäftigen, Lösungsansätze vorgestellt werden, die erstmal provozieren, aber auch zum Nachdenken anregen können. So sind bereits bestätigt die Vorträge von Prof. Wolfgang Kröger (ETHZ) über "Neuartige Kernkraft" und von Prof. Erich Windhab (ETHZ) über "Gepflanztes Fleisch aus dem 3D-Drucker"', während Vorträge zum Thema "Wald- statt Grasland", aber auch das Nachdenken über "Verzicht' im Sinne von 'Retour à l'ascèse'" noch bestätigt werden müssen. Man sieht, dass hier die ingeniöse, aber auch knorrige Art Bürgis als Vorbild dient, mit wissenschaftlich fundierten, aber gesellschaftlich noch nicht akzeptierten Ideen Denkanstösse und progressive Unruhe bei uns allen auszulösen.

Details finden Sie bitte unter https://www.jostbuergi.com/

Bernhard Braunecker

Über den Stellenwert scheinbar vergessener Renaissance-Gelehrter

Das Referat von Philipp Schöbi am 20. März 2020 in Zürich (siehe unten) trägt den bezeichnenden Untertitel ‚Über zwei schier vergessene Genies aus unserer Gegend' und weist auf verblüffende Gemeinsamkeiten des im Jahre 1514 in Feldkirch (A) geborenen Georg Joachim Rheticus mit dem im Jahre 1552 in Lichtensteig geborenen Jost Bürgi hin. Die räumliche Nähe ihrer Geburt und die nur leicht verschobene Lebenszeit erlauben uns, beide Biographien vom selben historischen Blickwinkel aus zu beurteilen. So hatten beide das grosse Glück, eng vertraut mit Geistesgrössen wie Kopernikus und Kepler zu arbeiten, deren kühne Denkansätze und Visionen sie aus nächster Nähe mitbekamen, und die sie zweifellos anspornten, mit Kritik und Ermunterung, aber auch mit neuen Ideen, Methoden und Instrumenten sich in die damals ablaufenden epochalen Erkenntnisprozesse einzubringen. Aber beide teilen sich auch das Schicksal des heute nahezu Vergessenen. Es ist das Anliegen der Bürgi Aktivitäten im toggenburgischen Lichtensteig und der Rheticus-Experten im vorarlbergischen Feldkirch, diese nicht hinzunehmende Schieflage in der Wissenschaftsgeschichte zu beheben. Nur wirken die historischen Klarstellungen auch ausserhalb der Bürgi- und Rheticusgemeinde?

Hier verblüfft nun die Meldung, dass im Juli 2016 bei Christie's in London eine von Rheticus signierte Erstausgabe seiner „Narratio Prima" von 1540 zum sagenhaften Preis von 1'818'500 Britischen Pfund (derzeit zirka 2'364'050 CHF) versteigert wurde.

Dies unterstreicht zweifellos die wissenschaftsgeschichtliche Bedeutung dieser Erstausgabe der von Rheticus stammenden ersten gedruckten Publikation der heliozentrischen Lehre. So heisst es bei Christie's zum Beispiel:

> *FIRST EDITION OF THE FIRST PRINTED ACCOUNT OF COPERNICUS'S HELIOCENTRIC THEORY OF THE UNIVERSE. Copernicus had allowed limited circulation of his preliminary theories in manuscript for*

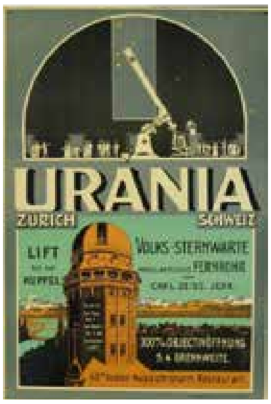
some years, but it was Rheticus whom he permitted and encouraged to write and publish a redaction of his ground-breaking science. The Narratio prima pre-dates by three years the publication of Copernicus's own De Revolutionibus orbium coelestium.

Laut der berühmten Auflistung von Owen Gingerich existieren weltweit nur noch 25 Exemplare dieses Werks, wovon lediglich zwei in privater Hand sind.

B. Braunecker, P. Schöbi

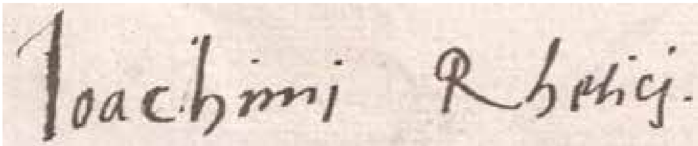
Jost Bürgi und Georg Joachim Rheticus

Über zwei schier vergessene Genies aus unserer Gegend



Die Aktivitäten zur Neupositionierung Bürgis in der Geschichte findet mittlerweile auch ausserhalb Lichtensteigs Beachtung. So lädt die ehrwürdige Astronomische Gesellschaft Urania Zürich den literaturwissenschaftlich tätigen Mathematiker und Rheticusbiographen Dr. Philipp Schöbi zum Vortrag am 20. März 2020 an der Uni in Zürich ein.
Den genauen Ort und die Zeit entnehmen Sie bitte der Webseite https://aguz.astronomie.ch. Dort finden Sie auch den Abstract zum Vortrag.

(Philipp Schöbi schrieb bereits in den *SPG Mitteilungen* Nr. 35 einen sehr interessanten Artikel über Rheticus, zu finden auch unter https://www.sps.ch/artikel/physik-anekdoten/rheticus-der-erste-kopernikaner-14/ .)



Winner of the Prix Schläfli 2019 in Physics of SCNAT

Dr. Matteo Fadel, winner of the SPS Award in General Physics 2019 (see *SPG Mitteilungen* Nr. 59, p. 4), won also this year's ***Prix Schläfli*** in the discipline "Physics" of the Swiss Academy of Sciences (SCNAT). In the following we print the laudatio written by the jury president Hans Peter Beck. The award ceremony took place on 5 November 2019 at the University of Basel, with a presentation of the awarded work "The Einstein-Podolsky-Rosen paradox in a many-body system".

The Jury of the Prix Schläfli Physics 2019 of the Swiss Academy of Sciences (SCNAT), consisting of Professors Hans Peter Beck (Universities of Bern and Fribourg, President), Christoph Bruder (University of Basel), Ruth Durrer (University of Geneva), Anna Fontcuberta (EPFL), and Christian Rüegg (PSI), has after a careful evaluation decided to bestow the Prix Schläfli 2019 in Physics to Dr. Matteo Fadel for his achievements in the field of fundamental quantum mechanics on the first demonstration of the EPR paradox and of Bell correlations in many-body systems with massive atomic ensembles.

The Jury decided unanimously to award the Prix Schläfli Physics 2019 to Dr. Matteo Fadel for his state-of-the-art contributions to both experimental and theoretical physics, leading to major breakthroughs in the understanding of quantum-mechanical many-body systems. Matte Fadel was first to demonstrate the Einstein-Podolsky-Rosen (EPR) paradox with an atomic ensemble. This paradox refers to a situation where measurement outcomes below the Heisenberg limit are predicted for a quantum system through measuring a different but with the former entangled quantum system. While the EPR paradox has previously been explored in optics and with single atoms, a demonstration with large ensembles of massive particles has not been reported previously. Moreover, this result opens up perspectives for applications in quantum metrology with enhanced measurement precision. Matteo Fadel was also first in observing Bell correlations in a many-body system. While Bell correlations of two particles have been observed in a variety of systems, a demonstration of Bell correlations in a true many-body system was unmatched before. This was possible in a new experiment measuring the correlated spin states of 480 Rb atoms in a Bose-Einstein condensate. This experiment was published in Science with Matteo as co-author [Schmied et al, Science 352, 441 (2016)]. A paper that received the 2017 Paul Ehrenfest Best Paper Award for Quantum Foundations, of the Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences for the most significant publication in the foundations of quantum mechanics published in the five calendar years prior to the prize call.

Dr. Matteo Fadel studied Physics at the University of Padova, Italy, where he received his BSc in 2011 with a thesis on "The black hole information loss problem". Fadel moved then to Zürich for his Master studies at ETHZ, which he concluded in 2013 with a thesis on the "Cryogenic setup for fast manipulation of the quantum motional states of trapped ions" under the supervision of Prof. Jonathan Home. In 2014, Fadel moved to Basel to work on his PhD thesis on "Many-particle entanglement, Einstein-Podolsky-Rosen steering and Bell correlations in Bose-Einstein condensates" under the supervision of Prof. Philipp Treutlein, which he concluded Summa cum Laude in 2018. Matteo Fadel is continuing his research in Basel as a Postdoctoral Research.

Physics Anecdotes (21)

The SPS did organize together with SCNAT a special symposium on 21 November 2019 in Bern, celebrating the 125th birthday of Georges Lemaître (see https://www.sps.ch/events/diverse-veranstaltungen/125th-anniversary-of-georges-lemaitre/ or the review on p. 27).

When discussing organizational details of the symposium I heard from our speakers *Harry Nussbaumer* and *Norbert Straumann* that they are in close contact with another well-known Lemaître expert, *Cormac O'Raifeartaigh* from Ireland. His father *Lochlainn O'Raifeartaigh* (1933 -2000) was professor at the Dublin Institute for Advanced Study DIAS, which was founded 1940 by the Irish state president Éamon de Valera with *Erwin Schrödinger* as its first head from 1940 until 1956. And I heard that Lochlainn had close connections to Switzerland.
In the following SPS honorary member Norbert Straumann will tell us more about the fruitful scientific relations between Zürich and Dublin, with Walter Heitler and Lochlainn O'Raifeartaigh as central persons.

B. Braunecker

The Dublin-Zürich Connection

Norbert Straumann

Walter Heitler in Dublin and Zürich

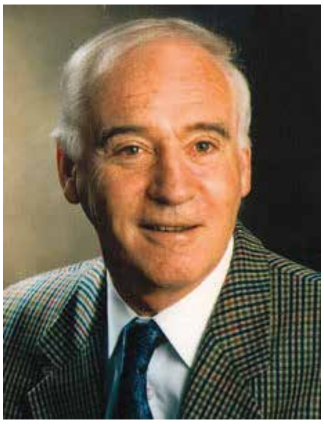
As background I recall that Heitler spent the years 1941-1949 at the Dublin Institute. Shortly after his arrival he became an Irish citizen. He retained this citizenship and his links with the country after he became Professor in Zürich as successor of Gregor Wentzel. His mother and his sister remained in Ireland until the end of their lives. Since Heitler's parents were both Jewish he had lost his position in Göttingen in 1933 and had to leave Germany. He spent some time in Bristol, was interned in 1939 for a while on the Isle of Man, and then soon received from Schrödinger an offer for a permanent position at the recently created DIAS. This was actually not the beginning of the Dublin-Zürich connection.


Walter Heitler (1904-1981)

Heitler had much interaction with Schrödinger at an early stage of his carrier. After he obtained his doctorate in Munich, Sommerfeld obtained for him a Rockefeller fellowship which he used to work with Schrödinger in Zürich, soon after the creation of wave mechanics. There he met Fritz London and the two young physicists developed the theory of the covalent bond. This happened when Heitler was 23 years old and opened him the door to Göttingen.


Erwin Schrödinger (1887-1961)

During his years in Dublin Heitler elaborated on his famous work on meson theory in collaboration with Hans Fröhlich and Nicolas Kemmer. For the first time he derived on the basis of isospin-invariance relations between some cross sections. But his most important work in Dublin was the theory of radiation damping and its application to cosmic ray physics. Several of his young collaborators, such as Walter Thirring, H. W. Peng, Cecile de Witt and Suraj Gupta later became international names.


Lochlainn O'Raifeartaigh (1933 -2000)

Encounters with Lochlainn O'Raifeartaigh

Lochlainn's Beginnings as a Scientist

In 1957, at the age of 24, Lochlainn was given a grant by DIAS to study under Walter Heitler at the University of Zürich. When Lochlainn arrived in Zürich, Pauli was still the dominant figure, and so he saw this great man in action, especially in the regular Theoretical Physics Seminar on Monday. This was at that time a gathering of the theoreticians from all over Switzerland; Stückelberg regularly came from Lausanne, and Markus Fierz from Basel. Res Jost had recently become professor at ETH and was successfully doing research on rigorous quantum field theory. I recall that he had just given his beautiful proof of a refined form of the CTP-theorem within Wightman's framework, which showed that the CTP symmetry holds if and only if the weak locality condition is satisfied.


ECG Stückelberg (1905-1984)

I was three years younger than Lochlainn, which is a lot at this early age. So, I saw him mostly in the theoretical seminar, but came into close contact with him only somewhat later after I got my diploma at ETH in 1959. Jost was the supervisor of my diploma work. Although the atmosphere around him was very stimulating, with some bright young collaborators in Jost's group (for instance David Ruelle), I wanted to work in particle physics that attracted me much more


Markus Fierz (1912-2006)

Res Jost (1918-1990)

than mathematical physics. So, I joined Heitler's group at the University, where I shared the office with Lochlainn and somebody in statistical physics.

Lochlainn worked intensively with Heitler on a nonlocal field theory that Heitler and Edmond Arnous had recently proposed. This also became the subject of Lochlainn's thesis. The background of this proposal was this: Heitler found himself rather out of sympathy with the renormalization program, in spite of its great success in QED. He considered it merely as a clever mathematical addendum to an already existing physical theory. In particular, he was concerned by the fact that it evaded the problems posed by the mass-differences of elementary particle multiplets, especially the proton-neutron mass difference. The latter was then also worked out by Lochlainn in the nonlocal theory of Arnous and Heitler. The whole enterprise was unsuccessful, but Heitler certainly addressed an important problem that remains unsolved; we have just shifted it to the quark level.

In my thesis I had to continue Lochlainn's work. Thanks to his hints and notes I quickly computed the mass difference of the pions - with no surprising result - and then that of the kaons. Heitler saw the results in a more positive light than me, but since not more than half a year had passed, he suggested that I should also do the Σ-hyperons in order to get my doctorate. Because I disliked in the meantime the Arnous-Heitler theory more and more, I did that also quite rapidly, hoping that I could afterwards do something more interesting. Still less than a year had passed, and so Heitler asked me to treat also the Ξ-hyperons. At that point I really got nervous and told Lochlainn that I had enough of all this nonlocal stuff with its intrinsic deceases. I never forgot Lochlainn's wise advice. He said: "Just slow down, do something else, and then Heitler will be satisfied after the year has passed". This is exactly what I did, and it worked. (Well, I did the Ξ-hyperons too.)

Heitler was, of course, very pleased with Lochlainn and tried to keep him. Not surprisingly, Lochlainn returned to DIAS in 1961 as an assistant professor. But the Dublin-Zürich-connection remained until the end of Lochlainn's life. Some members of this exchange (Andreas Wipf and Ivo Sachs) are in the audience. Unforgettable for me is the beautiful time in Dublin I spent soon after Lochlainn's return to DIAS. All of you who have worked with him know his passion for clarity and his ability to get to the essential features of a problem. He used to say that he first had to reach the stage when he could work on a problem in a bus or a tram, without using paper and pen. Above all we liked him as a human being, his kindness, honesty and simplicity. I had only few joint projects with him, but the most important was our common publication "*Gauge theory: Historical origins and some modern developments*", Rev. Mod. Phys., **72**, 1 (2000).
The unique personality of Heitler was honoured by Res Jost in his obituary: *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich* (1983) 128/2: 139-141.

Lochlainn as a Skier
Let me end with a story from a very nice week at a Winter School in Zuoz, a beautiful small town in the Engadin. This was much later in the seventies. Lochlainn had been before at a Winter School in Schladming, where he learned skiing with remarkable success. He was very eager to continue with this in the Oberengadin, a classic skiing region.

But let me first say something about his role at our school on "weak interactions and gauge theory". The audience consisted mostly of experimentalists, who were eager to understand the principles of gauge theories and their applications. The Standard Model was not yet fully established because of existing discrepancies with some experiments. Lochlainn did a great job. Quickly, the participants lost all fear to ask questions at any occasion. The interaction was really very intense. Years later people remembered this week as a very special one, during which they learned a lot. Lochlainn did everything at a relatively small blackboard, with only a few notes in his hands. He was the central figure of the school.

The afternoons were dedicated to skiing. We did quite demanding things, for instance from the Corvatsch, starting from over 3000 meters. Lochlainn enjoyed all this enormously, although he had to invest much more energy than an experienced skier. One day we went to the Diavolezza, where one has an exceptional view of the Bernina group. Lochlainn saw that some people were skiing over the Morteratsch glacier, and he asked me whether he would be able to do this too. Since he had been doing so well, I told him that this should be no problem, that skiing over the glacier is actually not so interesting, but very worthwhile because of the fantastic scenery. Initially things went fine. We crossed the main glacier, but then arrived at the top of a relatively steep slope. Lochlainn had done more demanding ones before, but now he recognized a bunch of crevasses at the bottom, some of which were quite big, emitting a bluish light. At that moment he got so scared that he was no more able to stand on his skies, after taking them off not even on his shoes. I could finally convince him to concentrate on his immediate neighborhood. Holding him, we then went step by step slowly downwards. At some point, when it became less steep, he lost all fear and we could continue on our skies. When arriving in the valley it was already darkening. Somebody from the school was eagerly waiting for us and brought us back to Zuoz.

A bit later in the evening we had our concluding banquet. Lochlainn was the obvious person to give the after-dinner speech. At the end of the successful school, the sympathy he had experienced, and the relief after the adventures of the day with a good end, Lochlainn was in a euphoric mood. He gave the best after-dinner speech I ever attended! Many years later, this time in summer, he came back to Zuoz together with his wife Trisha. In the afternoons we did some hiking. Of course, we also went to the Morteratsch glacier, over which he had been skiing years before. As you all know, Lochlainn was a keen hillwalker, so he enjoyed that too.

Journées de Réflexion der SATW

Adrian Sulzer, SATW, und Bernhard Braunecker

Die SPG ist Mitglied der Schweizerischen Akademie der technischen Wissenschaften SATW, zu deren Leistungsauftrag die Früherkennung von Technologien zählt. Das führt notwendigerweise zur Diskussion über Aktivitäten, die eine moderne Schweiz unternehmen sollte, um für die Zukunft gerüstet zu sein. Die alljährlich abgehaltenen *Journées de Réflexion* sind dafür ein geeignetes Forum, an dem sich Vorstand, Mitglieder des wissenschaftlichen Beirats, Leiterinnen und Leiter von Themenplattformen (TPF) sowie weitere Mitglieder und Mitarbeitende der SATW treffen, um strategische und thematische Fragen zu besprechen.

Künstliche Intelligenz

Verschiedene Vorträge prägten das diesjährige Treffen Ende Oktober: *Costas Bekas* von IBM Research Lab in Zürich rollte die Geschichte der Künstlichen Intelligenz (KI) auf und zog überraschende Vergleiche zur griechischen Mythologie. Er erklärte, wie sich die «Narrow AI» zur «Broad AI» entwickelte und skizzierte Potenziale einer «General AI», mit der er ab 2050 rechnet. Zwar sei KI den jeweils besten Fachleuten nicht überlegen – den übrigen 99 Prozent aber schon. Er sieht KI als Lösung für den «Data Overload» in der Wissenschaft und skizzierte, wie ein Forschungsprozess mit KI-Unterstützung künftig ablaufen könnte.

Diskussion der strategischen Fragen

Die Physikerin *Fabienne Marquis Weible*, die auch im SATW Vorstand tätig ist, eröffnete den strategischen Teil mit dem Titel: Technologie und die Herausforderungen unserer Gesellschaft. Sie plädierte für einen stärkeren Themenfokus, wobei man sich an den Sustainable Development Goals (SDGs) orientieren könne.

Der Physiker *Peter Seitz* (EPFL), ebenfalls SATW Vorstandsmitglied, präsentierte Vorschläge zur Gestaltung dieser Zusammenarbeit, basierend auf seiner Bedarfsanalyse bei Schweizer KMUs. So etwa die Gründung einer «Innovation Academy», ein Innovations-Coaching oder die Publikation branchenübergreifender Whitepapers (KI, Energie, Klima etc.). Man müsse die spezifischen Stärken der SATW genau identifizieren und darauf aufbauen. Auch soll man verstärkt mit Verbänden anderer Disziplinen (SPG?) zusammenarbeiten, denen man wiederum komplementäre Kompetenzen anbieten könne.

Vorstandsmitglied Peter Seitz sorgte mit seinen Vorschlägen für wichtige Impulse.

Wie legt man ein KKW still?

Stefan Klute, verantwortlich für Stilllegung und Entsorgung bei der BKW zeigte auf, wie das Kernkraftwerk Mühleberg stillgelegt wird. Spätestens am 20. Dezember 2019 beginnt der Prozess mit dem Ende des Leistungsbetriebs. Die BKW hat mit bis zu 300 Einsprachen gerechnet, de facto waren es nur acht. Ein Grund dafür sei die umfassende und transparente Kommunikation im Vorfeld gewesen. Auch Non Governmental Organisations NGOs wurden frühzeitig eingebunden. Finanziell sei das Projekt auf Kurs und die Schweiz agiere hier beispielhaft transparent. Er zeigte die technischen Schritte des Rückbaus auf. So werden etwa die Kerneinbauten unter Wasser auf Fassgrösse zerlegt und verpackt. Bei der Demontage werden konventionelle und radioaktive Materialströme klar getrennt. Der radioaktive Abfall wird nach Würenlingen transportiert. Insgesamt rechnet man mit ca. 200000 Tonnen Material, davon sind rund 7600 Tonnen unterschiedlich stark radioaktiv. Die BKW führt den Rückbau vornehmlich mit bestehenden Mitarbeitenden durch, was grosse Veränderungsbereitschaft abverlangt. Die Technik ist erprobt, doch für BKW, Schweizer Politik und Verwaltung handelt es sich um eine Pionierleistung.

Potenzielle künftige Betätigungsfelder

Anschliessend wurden vier Themengebiete mit Potenzial für die SATW vorgestellt. *Xaver Edelmann* machte den Auftakt zum Thema «Nachhaltige Kreislaufwirtschaft». Das Wirtschaftswachstum müsse von Ressourcenverbrauch und Umweltbelastung entkoppelt werden, wie es die SDGs vorsehen. *André Golliez* stellte das Konzept «Swiss Data Space» vor, das aktuell unter Beteiligung der SATW und diverser Bundesbehörden weiterentwickelt wird. Datenplattformen wie Facebook bedrohen die «digitale Selbstbestimmung» der Schweiz. Als Gegenentwurf umfasst der *Swiss Data Space* alle untereinander verknüpften und vertrauenswürdigen Schweizer Datenplattformen.

Patricia Deflorin, Leiterin der Themenplattform Industrie 4.0, zeigte aktuelle Chancen und Herausforderungen in Bezug auf das Thema auf: Dies umfasse viel mehr als die «smarte Fabrik». Nicht nur die Produktion, sondern die gesamte Wertschöpfungskette sei zu betrachten. Es gehe um eine Vielzahl an Technologien verschiedener Disziplinen mit unterschiedlichen Reifegraden. Folglich seien nicht nur die Potenziale gross, sondern auch die Unsicherheiten. Zudem gehen viele Firmen das Thema mit der falschen Motivation an: Sie konzentrieren sich auf Produktivitätsgewinne, während Innovationen nur eine untergeordnete Rolle spielen. Hier sei Unterstützung nötig.

Den Abschluss machte *Hans-Peter Meyer*, Leiter der TPF Biotechnologie. Er unterschied die fünf Arten der Biotechnologie mit ihren Märkten und Besonderheiten (siehe Tabelle).

Die Schweiz sei dabei unterschiedlich gut positioniert. So sei man in der roten Biotechnologie führend und habe bei der weissen grosses Potenzial. Bei der grünen hingegen sei die Situation aufgrund des Gentech-Moratoriums hoffnungslos. Die SATW könne bei Themen wie biobasierte Wertschöpfungsketten, Rohmaterialverfügbarkeit oder Kreislaufwirtschaft ansetzen.

Market	Color Code	Type of Products	Market Size	Companies
Pharma Biotechnology	Red Biotechnology	Monoclonal antibodies, other therapeutic proteins, vaccines, insulins, pDNA	> 170 Billion US$ CAGR 12%	> 6'000
Industrial Biotechnology	White Biotechnology	Small molecule pharma & fine chemicals, flavour & fragrance, bulk chemicals a.o.	60 Billion US$ without biofuels CAGR 6%	> 4'000
Agro Biotechnology	Green Biotechnology	Transgenic or genetically modified (GM) seeds and plants	15 Billion US$ CAGR 11%	100
Environmental Biotechnology	Grey Biotechnology	Environmental biotechnology, services & solution for bioremediation and waste treatment	< 1 Billion US$ CAGR 5-10%	< 50
Marine Biotechnology	Blue Biotechnology	Products and lead substances from the marine environment	2 Billion US$ CAGR 4%	< 50
Total Biotechnology Market	n.a.	All compounds produced by means of biotechnologies	> 250 Billion US$ CAGR 11%	10'600

Verschiedene Biotechnologietypen. Die Umsätze sind weltweit und pro Jahr zu verstehen.

Die SPG hat eine eigene Sektion ***Biophysik, Weiche Materie und Medizinische Physik***, die der volkswirtschaftlichen Bedeutung der Biowissenschaften Rechnung trägt. Physikalisches Verständnis und Modellierung, sowie neuzeitliche experimentelle Methoden tragen immer stärker dazu bei, biologische Abläufe auf atomarer Ebene, aber auch die Wechselwirkungen hochkomplexer Molekülstrukturen quantitativ zu beschreiben. Auf der SPG Webseite wird die Sektion wie folgt beschrieben:
Die Sektion hat als Ziel, Physiker aus diesem sehr interdisziplinären Themenkreis innerhalb der SPG zu vertreten und ihnen im Rahmen der wissenschaftlichen Sitzungen die Möglichkeit zu geben, ihre Forschung zu präsentieren. Die Sektion fokussiert sich thematisch auf die Gebiete der weichen Materie bis hin zur biologischen und medizinischen Physik und sie verbindet die Grundlagenphysik, beginnend auf atomaren und molekularen Niveau bis hin zur Komplexität der lebenden Materie und der lebenden Organismen. Diese sehr unterschiedliche Gemeinschaft hat weitreichende Interessen und umfasst auch viele verschiedene Techniken, die den Physikern sehr vertraut sind. Darüber hinaus sind sowohl experimentelle als auch theoretische Aktivitäten perfekt aufeinander abgestimmt und ihr Zusammenspiel ist für die Weiterentwicklung der verschiedenen Forschungsgebiete von grundlegender Bedeutung. Die Sektion soll junge Forscher anziehen und sie ermutigen, eine interdisziplinäre Forschung zu betreiben.

BB

IDL 2020

International Day of Light
16 May

Every year, UNESCO organises the Day of Light IDL on 16 May to highlight the important role of light in art, culture, education, science and technology today: https://www.lightday.org
The date commemorates the first laser by Theodore Maiman at Bell Labs in 1960 and therefore the 60th anniversary of this major event will be celebrated by IDL2020. The IDL aims in general are to promote the importance of the science and applications of light, to address challenges in sustainable development, health, education and to explain the importance of science education.

Since IDL2020 falls on a Saturday, there is a good opportunity to reach the public more efficiently than in other years and to inform them about the outstanding positive effects of photonics on all areas of our daily life. UNESCO encourages every one, every institution, to seize this opportunity, be it by organising a lecture or an open day to visit your lab, your company, your gallery, your school, your museum etc. You could then run your event using the IDL label free of charge and upload a short description to the IDL2020 calendar: https://www.lightday.org/events

If you need support, please don't hesitate to contact one of your national nodes: https://www.lightday.org/nodes

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The International Year of Light 2015 saw 13168 events in 147 countries, reaching 100s of millions.
As an enduring follow-up, the UNESCO General Conference in 2017 declared the 16 May as the International Day of Light. Over 1000 outreach events related to the theme of "light" in science and culture have taken place in 2018 and 2019 because of the International Day of Light. Over 90% of these are "new" events planned only for the International Day of Light.