

EUROPHYSICSNEWS

The magazine of the European Physical Society

Low Temperature Physics colder than ice



How industry
likes the EPS

Cryogenic detectors
essential in research

Science advocacy
career opportunity



edp sciences

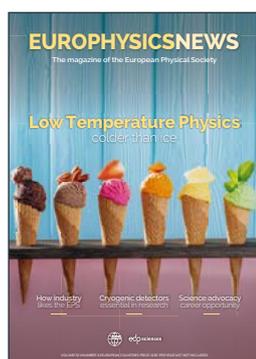
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Cover picture: Ice creams to celebrate the summer and the success of the amazing vaccines against COVID-19 and to underscore the focus of this EPN edition: low temperature physics. © iStockPhoto



▲ PAGE 06

Interview Maria Garcia Parajo



▲ PAGE 15

Quantum thermodynamics at low temperatures



▲ PAGE 25

Quantum storm in a cold cup

EPS EDITORIAL

- 03 On the importance of strengthening our relationships with industry
Luc Bergé

FROM THE EDITORS

- 04 Cool

IN THE SPOTLIGHTS

- 06 Maria Garcia Parajo - Laureate of the Winter 2020 EPS Emmy Noether Distinction
08 The Economics of Big Science

EPS NEWS

- 09 Associate Membership - Feedback of the EPS Survey 'Reaching Industry'

YOUNG MINDS

- 12 Science advocacy – a career opportunity for young scientists?
Enrique Sánchez

COLUMN

- 14 The European Microkelvin Platform

FEATURES

- 15 Quantum thermodynamics at low temperatures
Jukka P. Pekola
- 18 Cryogenic detectors exploring new phenomena in physics and astrophysics
Klaus Pretzl
- 22 Cryogenic Dark Matter Searches
Laura Baudis
- 25 Quantum storm in a cold cup
Carlo F. Barenghi and Ladislav Skrbek
- 28 Noble liquid calorimetry at the LHC and prospects of its application in future collider experiments
Martin Aleksa

COLUMN

- 32 Is there new physics around the corner?
Hans Peter Beck

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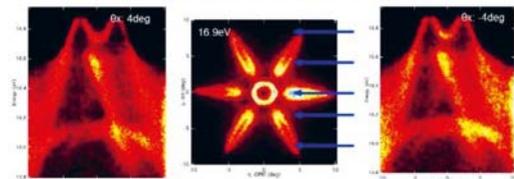
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The European Physical Society (EPS) is a non-profit association that advocates and promotes physics research and its contributions to the economic, technological, social and cultural advancement in Europe. Federating 42 national Member Societies, institutional and corporate Members from academia and industry, and more than 3'500 Individual Members, the EPS represents a community of more than 130'000 scientists. The scientific activities of the EPS are organised through 18 Divisions and Groups covering all branches of physics. The seat of the Society is in Mulhouse (France). Detailed information about the EPS can be found on www.eps.org.

THE EPS IS SEEKING A NEW SECRETARY GENERAL

to succeed the present Secretary General who plans to retire in spring 2023. Employment is expected to begin in autumn 2022 to allow for a thorough on-the-job training.

- The Secretary General heads the EPS Secretariat which supports the activities of the President, the Vice President, the Executive Committee, and all other bodies of the Society.
- The person to be recruited should have a university degree, preferably in physics or another field in natural sciences, with several years of experience in science management and

administration. A degree in political science, business administration or similar may also be suitable.

- The Secretary General shall be responsible for all administrative and financial matters of the EPS. The person supports the activities of the President, the Vice President, the Executive Committee, and all other bodies of the Society.
- The EPS is looking for a dynamic personality with leadership experience, excellent social and communication skills, and a strong interest in science policy and science advocacy, in particular at the European level. An enthusiastic commitment to the mission of the Society is expected. The position requires fluency in English, a working knowledge of French, flexible working hours, and availability to travel. A complete job description is available at <https://www.eps.org/recruitment>.
- The EPS offers competitive employment conditions commensurate with age and experience, in an attractive environment close to the French-German-Swiss border triangle. The financial conditions will be based on the salary grid of public research institutions in France.

Applications with a detailed letter of motivation and a Curriculum Vitae should be addressed not later than 30 June, 2021 to the EPS President, Dr. Luc Bergé (president@eps.org).

Further information may also be obtained from the present Secretary-General David Lee (d.lee@eps.org).



[EPS EDITORIAL]

On the importance of strengthening our relationships with industry

Since its creation in 1968, the European Physical Society (EPS) has been fulfilling its main missions of advocating physics research, providing independent input into science policy issues, supporting physicists and fostering international cooperation.

Among its numerous commitments, one of them needs to be strongly developed: that is our partnership with the industrial and technological tissue of our society. Barely mentioned in the EPS Strategic Plan 2010+, physicists in industry have, however, achieved tremendous advances of modern products that make our lives safer, better, and easier. The employment of young academic researchers who massively innovate in private companies is not a new practice.

For many years, several learned societies overseas have developed important programmes that aim at keeping their physics graduates who enter the private sector and at involving them closely in shaping their future. In the US, physics-based companies directly contributed \$2.3 trillion to the economy in 2016, led to 11.5 million employments, while 58% of all US physics graduates joined industry. In Europe, the thorough report “The importance of Physics to the Economics of Europe”, scanning the period 2011-2016, highlights that industry generated over 16% of the total turnover and 12% of overall employment in business economy. Additional EU statistics report that the demand for scientific professionals is expected to grow by 8% between 2013 and 2025.

Therefore, it is high time that the EPS adapts its offers, policy and services to efficiently partner with physics-based industrial organisations.

To start with, the Associate Members’ profiles, renewed a few years ago by including two new sponsorship levels, have been rendered more attractive for enterprises and technical universities. Organisations and companies of all sizes involved in physics research and in the development of scientific technologies are invited to become EPS Associate Members. They already benefit through the EPS from a broad audience at international scientific conferences, technology trade fairs, dense communication channels and

partnerships with key stakeholders and decision makers. In December 2020, the EPS launched a survey to reach a panel of companies and technical universities whose needs are centered on physics-based activities. We received more than 30% of feedback, with very constructive proposals, among which requests to organise meetings between students and industrial representatives, access to databases of young researchers and large facilities through a dedicated business platform, and open synergies between our various Associate Members. The result of the survey is detailed in an article of this EPN issue, inside a new section entitled “News From EPS” that will henceforth report items related to EPS management.

Following the recommendations sent through this survey, the EPS will undertake two major initiatives. First, together with our Member Societies and Divisions and Groups, we shall organise a one-day meeting starting the new EPS Forum and welcoming exhibitor stands, conferences, round tables, workshops and hands-on sessions conducted by industrial representatives and bringing together young researchers, renowned scientists, engineers and managers. Secondly, a professional web platform will be proposed to our Associate Members to access the broad EPS scientific and technological network of academic and industrial facilities, as well as to databases of professionals.

In parallel, the synergy with other learned societies to facilitate academic-industry ties will be encouraged. As an example, for young researchers willing to explore the ways to build up a startup company, the EPS Young Minds Committee in collaboration with The Optical Society (OSA) has recently organised a webinar series “From Ph.D to CEO” featuring young physicists – entrepreneurs who successfully leaped into business. We look forward to reading the Young Minds’ feedback on this exciting experience and expect a lot from their future contribution to the above EPS initiatives.

In conclusion, let us continue to reach out to our industrial colleagues! ■

■ Luc Bergé, *EPS President*

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[FROM THE EDITORS]

Cool

It is summertime in Europe. Thanks to the vaccines the COVID-19 pandemic is losing its strength. Like everyone else, physicists are eager to meet again in person, but the summer conferences – the traditional events where researchers meet, often at attractive locations – are still online. On the positive side, Europe is opening up for holiday travel and cool drinks on outdoor terraces.

After months of debates about how cool the vaccines had to be stored, this issue of EPN is even cooler with a set of articles about the field of low temperature physics in the millikelvin or even microkelvin range. The authors introduce you to the big questions in modern quantum thermodynamics and highlight the importance of cryogenic detectors in the search for dark matter or other (astro)physics phenomena. Quantum turbulence is the subject of an article with the most intriguing title 'Quantum storm in a cold cup'. Enough longreads to cool you down on a warm summer day. We thank our colleagues Christian Enss, Arnulf Quadt and Rüdiger Voss for article suggestions and the first proofreading.

Another cool item is the interview with Maria Garcia Parajo, the winner of this year's winter edition of the EPS Emmy Noether Prize. She is ICREA professor and leader of the Single Molecule Biophotonics group at the Institute of Photonic Sciences in Barcelona. In a chat with Kees van der Beek, chair of the jury, she speaks about her research and ambitions and the case of inequality in the physics community. She ends with expressing her concern about the young scientists who struggle with the impact of the pandemic.

Indeed this impact is a big concern, that the EPS Young Minds have addressed in earlier editions of EPN. This time they are more optimistic and present in their section the case of 'science advocacy' as a viable career opportunity for young physicists. Working for science amidst politicians and policy makers is another important and attractive way to serve physics and the physics community.

In the new section 'EPS News', the workgroup 'Reaching Industry' reports the results of a survey probing the interest of companies in an Associated EPS Membership. Strengthening the ties with industry is one of the spear points of Luc Bergé, the new EPS President. For EPN, the new section is an excellent opportunity to further strengthen its role of EPS magazine. Stay tuned for 'EPS News' in future EPN issues.

Indeed, EPN is a magazine made by physicists for physicists. In this issue many authors have made – again – a big effort to enthusiastically report their scientific stories and achievements. How cool is that!

We wish you a nice summer. ■



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Maria Garcia Parajo

Laureate of the Winter 2020 EPS Emmy Noether Distinction

Maria Garcia Parajo is ICREA professor and leader of the Single Molecule Biophotonics group at the Institute of Photonic Sciences in Barcelona. She is the winner of the Winter 2020 EPS Emmy Noether Distinction. Kees van der Beek, Chair of the jury, chatted with her about her research and ambitions, about role models and inequity in physics and – last but not least – the impact of the COVID pandemic. Here is her story.

Current research

“For the last ten years my team and I have been working on how the internal organisation, in space and in time, of biomolecules inside living cells regulate cellular functions. We develop optical techniques and instrumentation that have the necessary ultrahigh spatio-temporal resolution and sensitivity to detect individual molecules and the events relevant for cellular functions. Our research thus truly has two sides: the development of sophisticated optical and biophysical tools, and then, there is their application in the physiological context of living cells. In the first, we have the development of different far-field and near-field techniques for super-resolved imaging of individual molecules (on scales much smaller than those imposed by the diffraction limit of light). As far as applications are concerned, I wish to cite two examples, in which high spatio-temporal resolution is particularly important. The first is related to the pandemic. We all know that the COVID-19 virus has specific receptors on its outer shell; both the virus and the host cell membranes can be seen as ligands to these receptors. The manner in which the receptors organise themselves in space and time determines how strong the virus attaches to host cells. The spatio-temporal organisation of the receptors is therefore important to regulate the affinity of the virus to the host cells. Another example is the organisation of DNA or of chromatin inside the nucleus. This determines the basic mechanisms of the cell functions. We are particularly interested in the immune



▲ Maria Garcia Parajo. © Elena Enrique, ICFO, Barcelona

system and pathogen binding. Finally, there is the issue of cancer, which is intimately related to the migration and adhesion of rogue cells in sites where they do not belong. It is the deep and constant interplay of physics, physical binding mechanisms, and biology that fascinates me.”

Ambitions

“I followed a long trajectory, starting from electronic engineering. I quickly realised that the courses that fascinated me most were those that had to do with physics, including electromagnetism and solid-state physics. I therefore enrolled in a Physic Masters programme at my Alma Mater. All the

while, I was looking for opportunities to study solid-state physics, and chose a Master programme in semiconductor physics at Imperial College. For my PhD, I fabricated semiconducting quantum dots in III-V semiconductor heterostructures. One of the bottlenecks was that our fabrication process rendered these structures highly inhomogeneous. It was therefore very difficult to study their optical properties, e.g. through photoluminescence, since these were averaged out by material heterogeneity. This is why I searched for new approaches to study the photoluminescence of individual structures, and had the opportunity to pursue such during my post-doctoral appointments in Paris and in Twente in the Netherlands. The challenge in the latter group was to measure the fluorescence of individual (bio-) molecules at room temperature. A major breakthrough occurred through my interactions with Carl Figdor, an immunology professor at Nijmegen university. Together, we realised that my ultra-sensitive optical technique could be applied in living cells. For the first time, I could see the signal coming from bio-molecules, in vivo! This was something really new – a signal from a living, moving entity! From there, I became truly fascinated with the field that I have never left since.”

Role models

“I do not really know whether the people who have influenced me in my career choices, starting with my father, are actually role models or rather, inspirational figures. Unfortunately, having evolved in a very masculine academic

environment, I find no female figures among them. When I did my Ph.D. in London, there were only two women Ph.D candidates in the whole ten-story building! As for me giving inspiration to young scientists, this is a great and continuous source of pride for me. It is so extremely satisfactory to see students grow into scientific maturity, and to be able to create the environment and the conditions that have enabled them to do so, to modulate their inner capacities to this end! There are many facets to this route to scientific maturity, and I endeavour to accompany my students in every way, not only the scientific aspects. It is important to also address things such as emotions, fears, uncertainty, insecurity and self-confidence, to be in dialogue with one's students. My relation with the members of my group is thus very open. I am particularly proud of being a role model to young female scientists."

Recognition

"A couple of my colleagues had actually suggested that I would be a good candidate for the Emmy Noether Distinction. However, from there, during the nomination I was conscientiously kept out of the loop, and to be laureate was a very happy surprise. The distinction is important to me because it does not only recognise one's scientific career, but also all the extra effort that one has put into promoting and empowering women to excel in science. Through it, the European Physical Society recognises the specific importance of empowering women and promoting gender equity and that is very important to me."

Inequity in physics

"Definitely, nowadays young women are much more aware of their position than we were. They are much more aware of the things that they need not accept or take for granted. When I was a student, I took the fact that I evolved in a mainly male environment as a sort of "default" situation. I started to feel the resistance against my career progression at the point where I became



This was something really new – a signal from a living, moving entity! From there, I became truly fascinated with the field that I have never left since ”

a post-doc and then wanted to establish myself as a young professor, and I found myself competing for grants, for papers, for last authorship, for students. That was a tough part of my career – unfortunately, many young women researchers still find a particular resistance at that stage of their career today."

Remedies against inequity

"The problem of the position and career progression of women in physics is a very complicated one because it has a great many inputs. You therefore have to target many factors in parallel, something that will probably take generations. Yet, one of the most important things is that everyone, women and men, in the field is aware, is conscious of the implicit gender bias that still pervades our communities today and affects the working environment. It is the accumulation of many little things on a daily basis that causes women to snap and leave science. I really do believe that explicit bias is no longer the problem today. I also think that specific training courses in secondary and soft skills for women scientists are very important. Science is a highly competitive business and women have to acquire the necessary assertiveness, and the assurance to speak in public and put themselves on the front of the stage. Mentoring is also a very important point. Like I do with my students, it is necessary for more senior scientists to advise young women physicists how to handle uncertain, difficult or uncomfortable situations. On the other hand, I do not believe in positive discrimination or quota. To me, all discrimination is negative. Rather, as a way

to avoid discrimination, I would like to recommend the creation of specific calls for women scientists (physicists), in the same way as calls can be targeted towards age groups, *e.g.* early career researchers. In any case, one will always have to make that extra effort, that extra little thought, to ensure that women get equal chances at all levels, be it employment, conferences, or other."

The pandemic

"The pandemic is a major distraction from all points of view. We have had to stop all experiments. When we resumed, it was not the entire group that could return. Worse, in our case we are dealing with biological reagents; to obtain them afresh comes with major delays. 2020, however, has proved productive as far as data analysis and paper writing is concerned. I am afraid that the reduction of scientific productivity will be felt in 2021. More generally, we are all human so the pandemic affects us all. I have spent much more time giving emotional support to members of our group. Our group is very international, and many of its members went back to their home country, without always having the possibility to come back. To remain close to, and help our younger colleagues of the next generation is an extremely important part of our responsibility." ■

■ **Kees van der Beek,**
*Chair of the EPS Equal
Opportunity Committee*

▼ **Maria García Parajo.** © Elena Enrique, ICF0, Barcelona



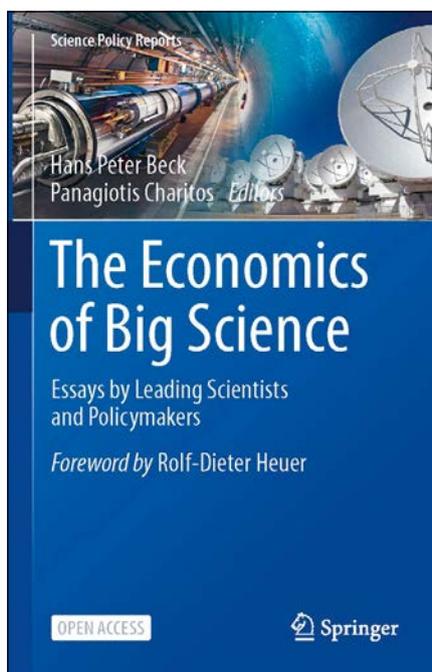
The Economics of Big Science

Our developed society is based on science and technology but only a minority of the people has an understanding of how they work. Equally unknown are the opportunities opened by fundamental research and their impact on our daily lives.

The history of science offers a wide range of examples of discoveries with unforeseen social value. It is worthwhile to remember the discovery of the delicate mechanism by which ozone is naturally produced and destroyed in the stratosphere. It illustrates one of the first evidences of Earth's vulnerability under human stewardship, but is also an illustration of the human capability to avoid vulnerabilities by making use of basic science with a mixture of scientific curiosity and a touch of environmental awareness. Scientific endeavour means very often exploring unknown territories. Here, its strengths lies in its capability for developing self-correcting strategies based on available evidence to explore the limits of science and the science of limits.

The book 'The Economics of Big Science' addresses the opportunities of research infrastructures and big-science projects for the generation of cutting-edge knowledge that translates into the virtuous circle entangling basic and applied research and their implications in economic progress. The essays, prepared by a unique panel of leading scientists involved in big scientific projects, economists, philosophers and policy makers, are based on detailed and in-depth analyses to illustrate to a wide audience the strong links between basic research and its social impact. Social progress addressing the world's most challenging open issues depends on the complex and multi-disciplinary interaction between science, politics and economics. Political, economic and ethical considerations have an influence on what is done with scientific discoveries, on how different fundamental science and technological developments are prioritised and on their contribution to social justice and global collaboration.

The essays examine the characteristics of big science facilities and their contributions in different areas such as: i) the use of state-of-the-art scientific and computing infrastructures that create products and services



with socio-economic impact; ii) the emergence of new discoveries that drives disruptive changes to our understanding of nature and economy; iii) the long-term sustainability and socio-economy of large-scale infrastructures; and last but not least, iv) the training of the next generation of scientists and engineers, the human factor that profits from large-scale infrastructures. While each research infrastructure and big-science project has a different socio-economic context involving different technological and political issues, they all have one thing in common: they require long-term perspectives with sustained investment and effective governance.

After reading the book, it is clear to me that as long as the flow of research to answer the deepest and most basic questions is not decreasing, industry is also neither stopping nor even slowing down, as new discoveries and disruptive technologies continue to emerge, delivering intellectual and economic progress.

Alternative ways of expressing the same idea exist. I tried to follow as close as

possible the original wording. The reader will find some answers to key questions such as: Where will we end up if we do not support scientific infrastructures as the driving force to understanding nature and to economic development? What are the options, power gains and vulnerabilities along with technological developments? What are the synergies between big scientific organisations and public and private funding organisations? What is the socio-economic impact of curiosity-driven research in the digital and green transition? How to foster all the assets of research infrastructures including the translation of research from academia to industry? How does small-scale science benefit from large-scale research infrastructures.

The essays in the book show that we need large-scale infrastructures for basic research and innovation and for supporting the industrial market. The sustainment of big-science infrastructures is a challenge that requires long-term social support and global collaboration increasingly coupled to the assessment of their socio-economic and scientific impact. A challenge that requires a multi-decade approach with sustained policies and scientific strategies that strengthen the mutually beneficial relationship between science education, fundamental research and technological and industrial innovation. The book contributes, with stimulating reflections, to highlighting newly acquired research-based powers that open opportunities for science and society. ■

■ **Carlos Hidalgo**

Laboratorio Nacional de Fusión, CIEMAT

Reference

'The Economics of Big Science – Essays by Leading Scientists and Policymakers', Editors: Hans Peter Beck and Panagiotis Charitos, DOI ebook (Open Access): 10.1007/978-3-030-52391-6

Associate Membership

Feedback of the EPS Survey 'Reaching Industry'

Organisations and companies of all sizes in the public or private sectors, which are involved in physics research or in the development of physics-based technologies, are invited to become EPS Associated Members. The EPS Workgroup 'Reaching Industry' launched a survey to probe the interest in Associated Membership. We report here the results.

EPS Associate Members (AM) benefit from the unique EPS platform for creating partnerships with key stakeholders such as industry insiders and decision makers interested in physics and in addressing societal grand challenges. They have the opportunity to contribute directly to focussed actions involving a broad audience at international scientific conferences, technology trade fairs, and similar events.

EPS plans to improve its collaboration with industrial partners, as they are fundamental for translating basic research into innovation, products, and businesses creating value and impact for society. In the US, more than 50% of physics graduates are working in the private sector [1]. In the EU, physics-based industries produce 16% of business revenue, 2/3 of which is generated in Germany, UK, France, and Italy [2]. Other statistics show that the demand for Science, Technology, Engineering and Mathematics (STEM) professionals and associate ones is expected to grow by 8% between 2013 and 2025, whilst the average growth forecast for all occupations is 3%. Employment forecast in STEM-related sectors shows a similar trend: in 2015 it was estimated to rise by 6.5% between 2013 and 2025, although with huge differences across sectors [3]. In parallel, in the past years, Europe has been experiencing a decline in the number of students opting for STEM careers [4].

EPS would like to contribute to mitigating this trend. In 2021, the EPS will propose new initiatives serving

industrial physicists and educating students about jobs in industry. For this, a dedicated staff member at the EPS secretariat was appointed. An EPS workgroup - "Reaching Industry" - is moreover engaged in actions for the recruitment of Associate Members affiliated to physics-based companies and technical universities. Between December 2020 and March 2021 a questionnaire was sent to a panel of enterprises, technical high schools and universities. The goal of this questionnaire was to probe their interest in becoming EPS AMs in the coming years.

The questionnaire comprised six questions, requesting the opinion of the respondents on the suitability of the present AM programme and related membership fees to their current needs. It asked also for possible proposals to enhance the EPS current offers, for their interest in joining our Society as AM and for which component of our learned society they would like to work (<https://ec.europa.eu/eusurvey/runner/EPS-AM>).

As displayed in figure 1, the survey was sent to a selection of 62 organisations, composed of 10 regular EPS exhibitors at EPS conferences, 10 companies earlier approached by the Industrial Liaison Office of the Istituto Nazionale di Fisica Nucleare (INFN/ILO), 12 Multinational and Small & Middle-sized Enterprises, 12 Technical Universities from Western Europe and 18 Technical Institutes - many of them being located in Eastern Europe - proposed by the EPS Young Minds Action Committee.

We received feedback from 37% of those who were contacted, and by March 1, 29% returned the questionnaire with complete answers. The distribution of respondents by European nation - even beyond - is detailed in the graphics below. Two of them manifested their interest in joining us within this year as new AM of the EPS. Two others expressed their interest to join next year, due to the pandemic situation.



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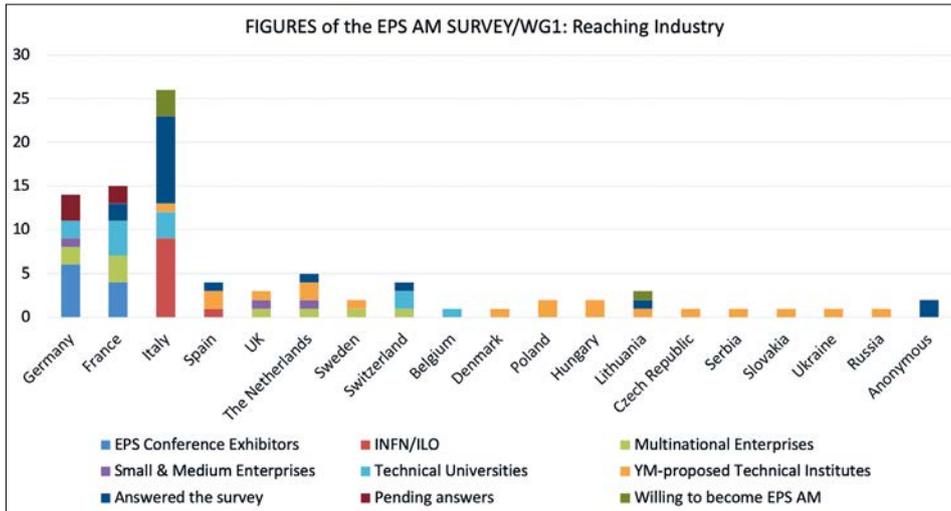
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What emerged from the survey is a common and repeated interest for the following activities:

- Organisation of meetings or workshops between researchers and industrial representatives
- Access to exhibits of top-level physics conferences at discount rates
- Free access to scientific articles and reviews on topics of interest
- Information on upcoming EPS conferences
- Access to a database of bachelor/master students, PhD students and postdoctoral fellows for employment or internships
- Job offers available on an on-line platform.

As a reminder, EPS proposes three levels of Associate Membership (Prestige Sponsor, Sponsor for Societal Challenges, Supporter Associate Member), providing customised packages of benefits, prominently highlighted through multiple communication channels and well acknowledged for their commitment (www.eps.org/page/membership_am):

1. The **Prestige Sponsorship** for organisations that wish to sponsor the most prestigious prizes of the Society for outstanding contributions to physics. This category also makes it possible to create new awards tailored to the own field of interest and strategies of the AM.

2. The **Sponsorship for Societal Challenges** for organisations that wish to support early career researchers in Europe, promote physics education, equal opportunities and/or physics for development.
3. The **Supporter Associate Membership** for small and medium-sized organisations that are seeking global exposure through EPS networks and events.

Most of the respondents did not make any definitive choice yet, even if a clear preference was expressed to join the AM categories 2 and 3.

As potential EPS Associate Member, the contacted companies and technical institutes proposed specific actions for adding higher value to their organisation. These could be priority actions developed together with the EPS, such as:

- Initiatives to support early career researchers in Europe and promote physics education
- Meetings and webinars to share interests and needs with other associate members or researchers
- Opportunities to participate in scientific and industrial research projects with other partners
- Creation of new consortia to participate in EU project calls.

The EPS acknowledged these suggestions and decided that, in addition to the rights and benefits linked to the above categories of membership, new

advantages will be proposed in the future for all AMs, namely,

- Discount rates for exhibitor stands and for participation in plenary talks, round tables, workshops and hands-on sessions during EPS Forums that will bring together young researchers, renowned experts and physics-based companies
- Access to the broad EPS scientific and technological network of academic and industrial facilities, as well as to databases of professionals
- Free access to Europhysics conferences dedicated to technological developments
- Free-of-charge publication and consultation of job offers on EPS dedicated websites
- Participation to career development and societal (e.g., citizen science) meetings.

The present authors wish to thank again all the respondents for their important participation to the questionnaire and hope, with these new offers, to make EPS more attractive to physicists and engineers from the industry.

If you wish to join the EPS in this renewed framework of collaboration, do not hesitate to contact us at president@eps.org or ophelia.fornari@eps.org for complementary information. ■

■ **Luc Bergé, Ophélie Fornari, Eugenio Nappi, Christophe Rossel, Pablo Garcia Tello,**
Workgroup 1 – “Reaching Industry”

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Oxford Instruments Nanoscience supports the Institute of Science and Technology Austria with its future research

The Institute of Science and Technology Austria (IST Austria) is a PhD-granting research institution that spans the areas of mathematical and physical sciences, life sciences, and information and data science. The Thermodynamics of Quantum Materials (TQM) research group at IST Austria develops new techniques that get to the heart of quantum materials. The group required two new superconducting magnet systems to enhance their cutting-edge research and turned to Oxford Instruments NanoScience for the job.

Kimberly Modic, Assistant Professor at IST Austria, talks to Mercury Hao, Project Manager at Oxford Instruments NanoScience about IST's goals for future research, their investment in magnet technology and her experience of working with Oxford Instruments NanoScience.

What goals are you looking to achieve using Oxford Instruments NanoSciences' TelestronPT 12 and 14 T?

The TelestronPT 12 and 14 T will allow us to study the complex properties of quantum materials, while developing new highly-sensitive techniques. By shaking tiny, single crystals (of the order of 10-100 μm^3) on a resonating cantilever, we will be able to study the sample's magnetic properties as the crystal is reoriented in the magnetic field.

While designing the infrastructure and surrounding platforms for

our TelestronPTs, we've also been preparing the electronics and wiring for our first measurements, which we hope can begin over the summer.

What are your first impressions of the TelestronPT 12 and 14 T?

I am truly impressed with the quality of the TelestronPT systems and the support provided by Oxford Instruments. We had unique requirements due to the magnetic floors in our laboratory, and this resulted in the creation of a motorised lifting frame to raise the entire cryostat and 14 T magnet from the floor when in operation. When the magnets are switched off, the system can be lowered back to the floor, creating enough space above the magnet to exchange samples.

What has been your experience working with Oxford Instruments?

The team at Oxford Instruments NanoScience put our minds at



▲ Oxford Instruments TelestronPT

▼ TelestronPT frame installation

ease during each stage of the order and installation process, and were competent, dependable, and personable throughout. Any concerns that were raised during the planning stages were resolved promptly, and the entire system has exceeded expectations. As a new faculty member, I was excited to set up my own laboratory and most importantly, wanted the installation to go smoothly - but I never expected that I would be able to sit back and relax for the majority of the process! The team has been incredibly efficient, goal-oriented, and professional throughout, and truly cares about the integrity of the system just as much, if not more, than we do.

All in all, we're really excited to start using the TelestronPT 12 and 14 T, so watch this space! ■





Science advocacy – a career opportunity for young scientists?

■ Enrique Sánchez, EPS

New generations of scientists are struggling to develop their professional careers. Enrique Sánchez Bautista, policy officer at the European Physical Society, reflects on the career bottleneck in academia and on opportunities for scientists to engage in policy making, which requires more than ever skills such as PhD students have.

The career bottleneck in academia

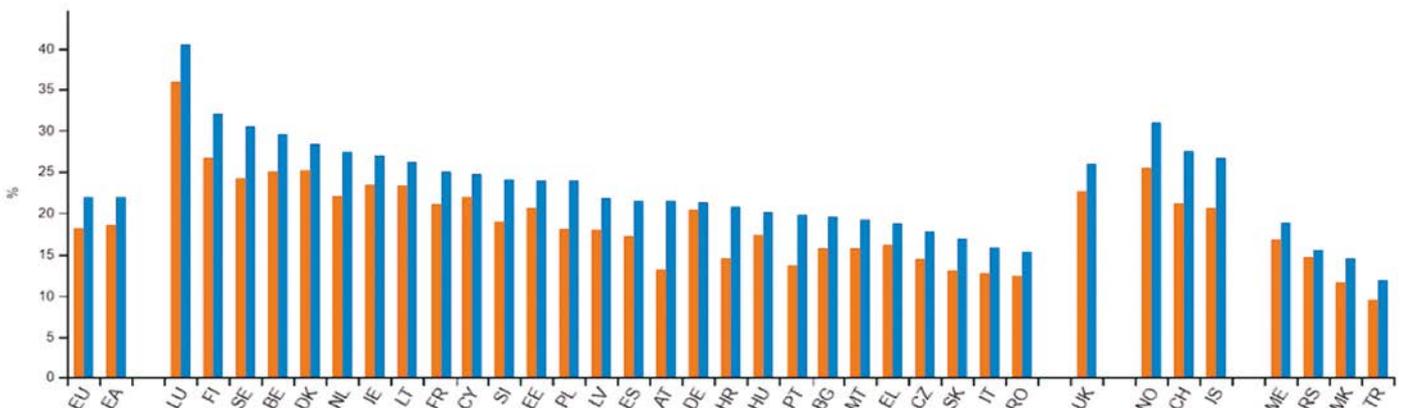
The increase of the number of researchers, other professionals in science and technology and doctorate/PhD students in the European Union [1] coincides with a remarkable increase in the number of researchers with temporary employment contracts. There has not been a similar increase in the number of tenured positions before; we are seeing an increasing career bottleneck in academia. For instance, the National Institutes of Health reported nearly 60% more researchers in the life sciences below the age of 35 in 2001, compared with figures in 1993, yet the number of tenure-track positions grew by only 6.7%. A study in Belgium shows a similar trend, arriving at a ratio of 3.2 doctoral candidates for every faculty position [2].

▼ Increase of people who have a tertiary education between 2012 (orange) and 2019 (blue).
Source: Eurostat

To mitigate this career bottleneck, active public policies must be considered to attract and retain PhD students because society has invested heavily in their education and training and they represent a highly skilled workforce. Involving these young professionals in the modernisation of higher education and in the internationalisation of the economy [3] needs to be a priority for European policy makers. A broad range of stakeholders may play a critical role in the process requiring new economic actors and instruments with the capacity to invest in and employ doctorate holders. At the national levels these actors have come together and developed collaborative approaches to retain knowledge and talent in Europe.

Motivated by the concerns, initiatives have emerged to adapt the training of doctoral students to the needs of the current social and markets in an attempt to alleviate the lack of career options for PhD students. As such, in PhD programmes in scientific disciplines courses have been shortened and adapted to include opportunities for putting research into its wider context [4].

Fostering the actions of better cooperation systems is a challenge. Academia, Research & Technology Organisations, funding agencies, learned societies, policy makers, and other stakeholders are encouraged to jointly discuss recommendations to improve the situation [5]. The introduction of doctorates awarded through ‘Innovative Training Networks’ and



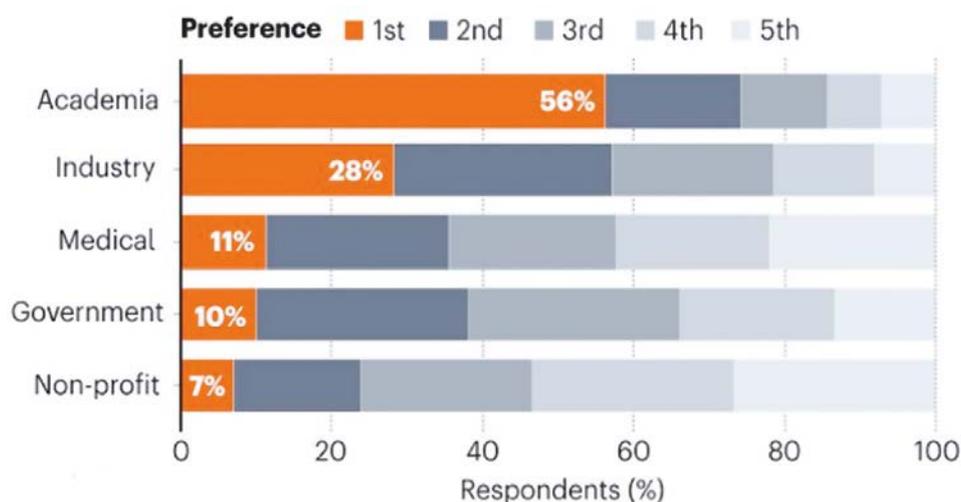
postdoctoral fellowships in the 'Society and Enterprise' panel of the European Commission's Marie Skłodowska Curie Actions is an example of cooperation encompassed in the European Framework Programmes. The interdisciplinary nature of these positions allows candidates to diversify their competencies and experiences, expand their professional network and gain wider labour market awareness.

Despite the global job crunch, a large fraction of PhD students remains engaged in research [6]. Figure 2 shows that most of the PhD students continue to aspire to an academic career [7]. This survey points out that institutions must adapt to the needs of PhDs students.

Since 2001, the European Commission (EC) has put the focus on the career development of researchers as an integral part of establishing the European Research Area (ERA). The first specific policy document was the communication Research – One Profession, Multiple Careers [8] (EC 2003). There was explicit recognition of the need for complementary skills and training for PhD students and researchers [9]. The ERA called Member States and the European Commission to share and develop evaluation and appraisal systems, improve working conditions for researchers and stimulate intersectoral mobility of researchers, as stated in the draft published in January 2021 by the European Council, which stressed the importance of the development of the labour market for researchers in Europe [10].

Becoming a science advocate

Very interesting options are those concerning science advocacy contributing to the cooperation between academia and policy makers. Scientists have excellent bases to assist governments in developing policy related to science and technology. The lack of a formal career path may seem like a



▲ Preference of PhD students for the next step in their professional career. Source: Nature PhD Survey 2019

major barrier, but institutions such as the European Physical Society and European Institutions such as the EC, offer opportunities to young researchers to be involved in the European policy making ecosystem and to contribute to the decision-making process using their deep expertise in specific fields.

As a former member of the Young Minds Programme and following several years in research in the field of experimental quantum physics, I moved to Brussels and started a traineeship in the Space Programmes Directorate at the EC. There, I realised the strong need of the European Institutions for a well-educated STEM workforce, in order to provide a continuous supply of researchers trained at the forefront of advances in Science and Technology, that can contribute to a better development of the scientific policies and lead the EU towards a competitive knowledge-based economy. Thus, right after finishing the traineeship programme I started supporting the EPS in building its strategy at the European level and became an advocate on behalf of the European physics community representing its interest towards the European institutions.

Bearing in mind that technology sovereignty is becoming a major consideration where the lines between science, technology, and security are emerging as a major concern, the

engagement of well-trained scientists involved from the start in the policy-making process is more important than ever, in order to help connect the lines between these three above-mentioned independent but intertwined concepts. ■

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by Christian Enss

Coordinator of the European Microkelvin Platform – DOI: <https://doi.org/10.1051/ejn/2021301>

The European Microkelvin Platform

Zeroing in on zero to create new research opportunities in fundamental physics and materials science and to advance and exploit novel technologies are the aims of the European Microkelvin Platform (EMP). This is a consortium of eight leading ultralow-temperature laboratories and nine technology partners and companies across Europe.

The environment of ultralow temperatures, where the thermal energy is so small that the quantum nature of materials becomes evident on large scales, is and has been a breeding ground of innovations. A well-known example is superconductivity – a state of matter, first observed at very low temperatures in elementary metals, is now a vast field of research of large societal importance, as evidenced by its use in power generation, commodity searches, transportation, and medical imaging, to name just a few. Typical for the quantum technology field, this list grows constantly, as methods based on superconductivity advance and new materials are discovered. Superconductivity is just one example of many extraordinary states of matter that can ideally be explored or even discovered at ultra-low temperatures, and which have the potential to influence everyday life by leading to novel technologies that are hard to envision today. This is very much a frontier field and as the quest for even lower temperatures continually advances, as yet unknown, novel and potentially exploitable states of matter will inevitably emerge.

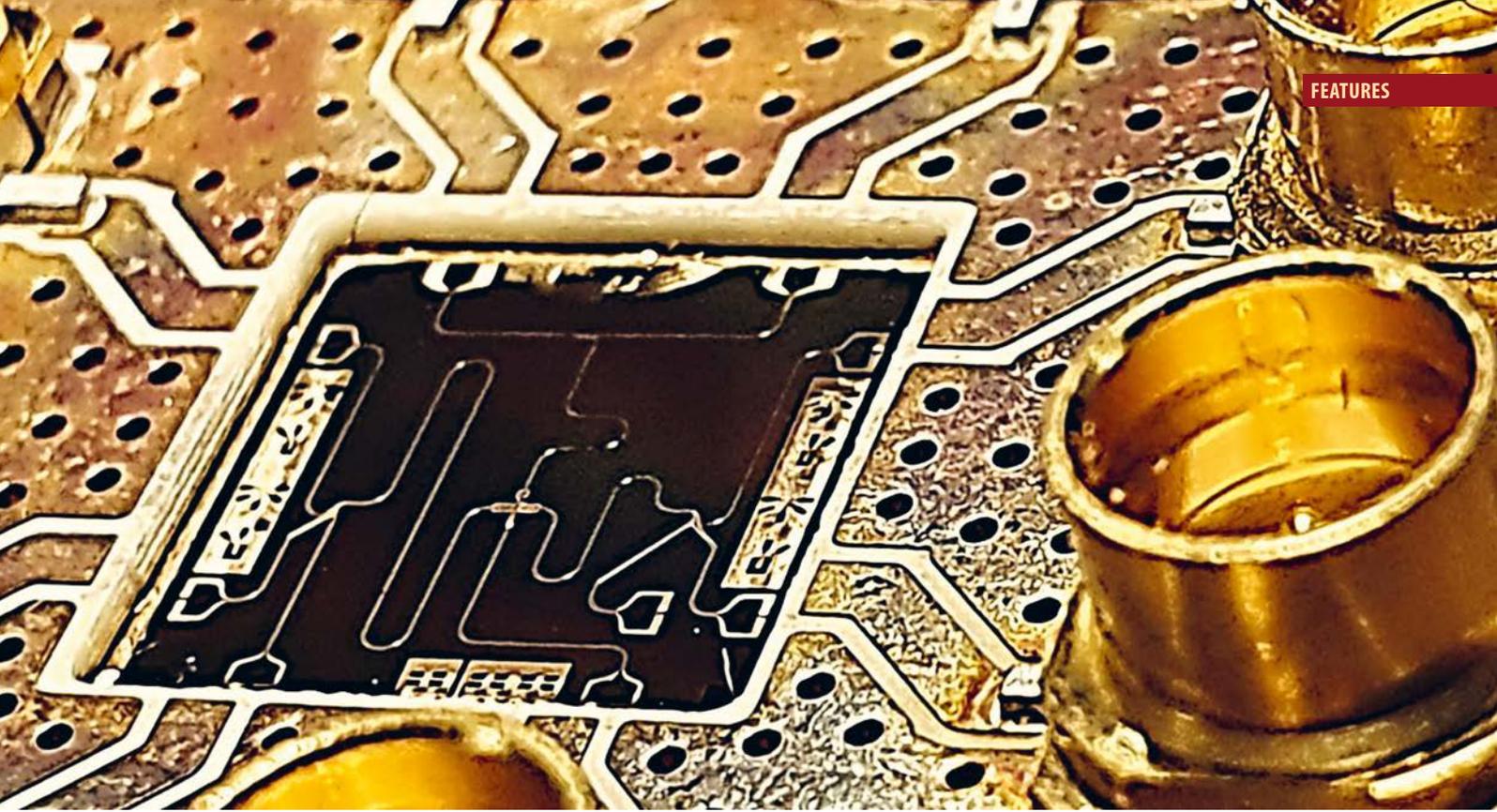
The EMP unites, coordinates and reinforces all existing European large-scale ultralow temperature research infrastructures in a single body and make them available to the scientific community. The individual members offer a diverse and comprehensive portfolio of experimental expertise, with eight of them opening their facilities to external researchers across the

disciplines from academic institutions and companies who do not have their own infrastructure. Combined, the EMP laboratories offer the most comprehensive portfolio of cryogenic facilities worldwide. Users can apply for measuring time at EMP to pursue their own scientific ideas and projects. User access is supported by the European Union's Horizon 2020 Research and Innovation Programme. Approved user projects at EMP facilities are free of charge. In addition, travel as well as local expenses of users are covered and the EMP provides logistical and technical support if needed (see: <http://www.emplatform.eu/>).

A very important component of the EMP program comprises innovation projects, which are carried out in partnership between academic institutions and companies. These have been initiated to maximize the impact of the EMP research and to expedite bringing to market new products based on the technology arising from the program as quickly as possible. Several new devices based on quantum technology have been developed, enabling ultra-sensitive energy detection, magnetic flux measurement, and amplification at the quantum limit to name just a few. The consortium has already launched its first new spin-off company, "Basel Precision Instruments" from Basel University. The initial success of several of their new instruments exceeded all expectations, with the first production series being briskly sold out, necessitating a rapid ramp-up in production.

The overall objectives of the consortium are to enhance and widen the integration of the leading ultralow temperature facilities in Europe under the umbrella of the European Microkelvin Platform which will lead to strengthening Europe's international leadership in ultralow temperature studies and technology.





QUANTUM THERMODYNAMICS AT LOW TEMPERATURES

■ **Jukka P. Pekola** – DOI: <https://doi.org/10.1051/e pn/2021302>

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Low temperature phenomena and methods are quantum thermodynamics per se. Modern engineered quantum systems, for instance those used for superconducting quantum information processing and mesoscopic electron transport, provide working media for realizing devices such as quantum heat engines and refrigerators and a testbed for fundamental principles and phenomena in thermodynamics of quantum systems and processes.

Quantum Thermodynamics?

Quantum thermodynamics presents an interplay and coexistence of quantum mechanics and thermodynamics, the two perhaps antagonist avenues in physics. It has existed as a field of science already for some time, most notably under the title “open quantum systems”. This discipline describes genuinely quantum mechanical systems interacting with external world. The latter can often be considered as classical in nature, providing a heat bath or a collection of such baths. The position that we take here for describing quantum thermodynamics is to make it a synonym with “thermodynamics of quantum systems and processes”.

Low temperature domain

Our focus in this article is the low temperature environment, typically in the sub-kelvin regime. Foundational developments, experiments and technology in low temperature physics, like the various refrigeration techniques, magnetic phenomena, thermometry *etc.* are to be considered quantum thermodynamics (much ●●●

▲ **FIG 1:** A photo of a typical experimental setup housing a superconducting quantum circuit. Sample holder with RF-connectors carries the chip in the middle. At the very centre, a cross-shaped transmon-type superconducting qubit couples capacitively to coplanar wave resonators acting as harmonic oscillators. For a quantum thermodynamics experiment, *e.g.* in [4], the resonators are terminated by on-chip resistors (too small to see in this photo) that act as heat baths or absorbers of heat. The overall size of the square-shaped chip in the centre is 7 mm x 7 mm. (Photograph courtesy of Bayan Karimi.)

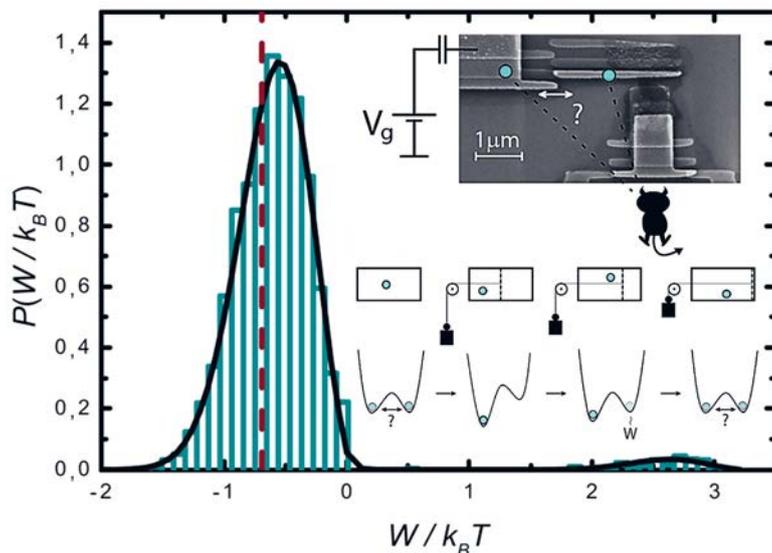


How to build quantum heat engines and refrigerators where the working substance obeys (nearly) coherent quantum dynamics? In this context, can one find "quantum supremacy" in form of higher powers and efficiencies as compared to classical reference devices? ”

●●● before the name was coined), especially in the sub-kelvin temperature range [1]. One can thus say that quantum thermodynamics experiments have a century old history by now, ever since the cryogenic liquefaction of gases and discoveries of superconductivity.

Low temperatures provide a unique setting for quantum thermodynamics. Different physical sub-systems (phonons, electrons, nuclei among others) are typically weakly coupled to each other and their properties can be controlled and monitored individually, with relatively slow relaxation times amenable for experiments. But what brings yet another important twist to this story is the development of experimental techniques in the fields of micro- and nanofabrication, quantum information devices (e.g. superconducting qubits), and mesoscopic transport in electronic circuits. Local probing of particles, the quantum states and temperature are key ingredients for successful experiments. Activity and investments in these related areas have facilitated the emergence of a new field of research, the circuit quantum thermodynamics (cQTD).

▼ **FIG 2:** Mesoscopic single-electron boxes and transistors are next to ideal tools for stochastic thermodynamics experiments at low temperatures [2]. They allow for accurate determination of heat and work, and the experiments can easily be repeated many times, up to millions of repetitions, for collecting reliable statistics. Here a single electron box is monitored by a single-electron electrometer. By electrometer observation and feedback process the concept of Szilard's engine (lower inset), a form of Maxwell's demon, can be realized [3]. The main frame demonstrates apparent violation of the second law in the traditional sense: average work W done in a Szilard's engine cycle is negative because of the information gained by the observer (electrometer). (Figure adapted from [3].)



Selected toolbox for quantum thermodynamics experiments

Being a little biased one might say that the birth of quantum thermodynamics experiments at low temperatures took place with the stochastic thermodynamics experiments on quantum dot and single-electron box circuits [2]. Yet the “quantumness” of these experiments can be debated since their dynamics at low operation frequencies, as applied in the experiments, follows classical rate equations. The remarkable advantage of these setups is that the (charged) particles can be followed one by one with high resolution using ultrasensitive electrometers, and their energetics is governed by a simple Hamiltonian determined by the electrostatic charging energies. The outcome of these experiments was, first of all, verification of common fluctuation relations (relations that imply the first and second law of thermodynamics for stochastic processes) with unprecedented accuracy, and demonstrations of both non-autonomous and autonomous Maxwell's demons, shedding light to the almost two centuries old puzzle of the relation between information and energy [3]. The question of the minimal cost in computing was also addressed. This is the Landauer bound, where the energy cost equals Boltzmann constant k_B times temperature T times $\ln(2)$, $k_B T \ln(2)$, per bit in a quasistatic process.

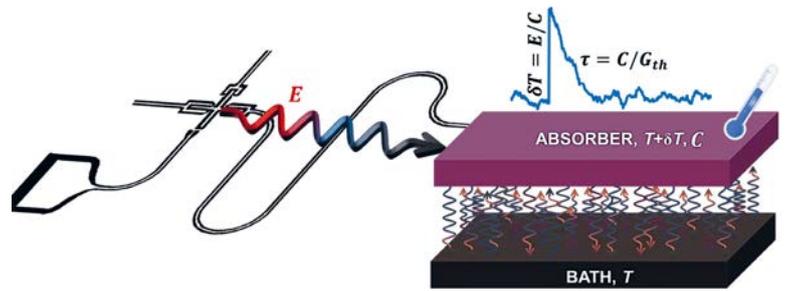
The stochastic thermodynamics experiments by monitoring and counting particles (charges) are operating mostly based on classical physics. Besides this, they give only indirect information about heat and work, hinging on the model, in other words the Hamiltonian, of the system under study. True thermodynamics, on the contrary, counts on direct observations of heat currents and temperatures, and power consumption of the sources. To achieve these capabilities, our laboratory has been working over the years to realize on-chip electronic thermal detectors realizing bolometry and calorimetry with ultrasensitive thermometry. Bolometry here means detection of steady-state heat currents, whose sources can be Joule dissipation, injection of hot carriers, or coupling to photonic or phononic degrees of freedom in the circuit. Calorimetry, on the other hand, refers to thermal detection of single events, like absorption or emission of a photon in the element whose temperature is monitored. In both these tasks one needs a capable thermometer with proper figures of merit. The remarkable advantage of low temperatures in thermodynamic experiments originates from the ability to realize energy absorbers, say with only 10^8 thermally distributed electrons in a metal, having an extremely small heat capacity (about $100k_B$ or less) and extremely weak thermal coupling to the phonon heat bath. Measuring steady-state heat currents with thermometers is based on a very simple principle: in a linear system the temperature change is directly proportional to heat current via thermal conductance like in Ohm's law where voltage is proportional to the current via conductance. On the other hand, calorimetric

principle is demonstrated in Fig. 3; currently its energy resolution in state-of-the-art experiments is already limited by the fundamental thermal fluctuations and not by the measurement apparatus.

We use thermal detectors for measuring energy dissipation in quantum circuits. Superconducting qubits based on standard Josephson junctions and resonators (harmonic oscillators) provide a basis for realization of a multitude of devices and experiments. Superconducting quantum technology has advanced enormously from the realization of the first superconducting qubits more than 20 years ago: this development offers us building blocks with versatile control options and very low internal dissipation and decoherence rates. By combining these circuits with the mesoscopic baths, *i.e.* the absorbers described above, one can then construct quantum heat valves, rectifiers, heat engines and refrigerators, and thermal masers, just to mention a few examples, and to address the scientific challenges described below.

Scientific questions

What are then the big questions in modern quantum thermodynamics? On a very general level, the question of how the laws of thermodynamics in the quantum setting are realized is an interesting issue. Classical stochastic thermodynamics stretches the traditional thermodynamics to a regime where fluctuations play an important role. Are the fluctuation relations governing these processes applicable to quantum systems, where the measurement and the measurement apparatus cannot be viewed as an innocent witness of what is happening in the system itself? How to measure work and heat in an open quantum system? One may also ask how to build quantum heat engines and refrigerators where the working substance obeys (nearly) coherent quantum dynamics? In this context, can one find “quantum supremacy” in form of higher powers and efficiencies as compared to classical reference devices? Currently there is no unanimous answer to this question: creating quantum coherences costs in general energy, *i.e.* one needs to do work to produce it, meaning that with the most obvious operation protocols coherent quantum dynamics is not useful. One topical objective in cQTD is how to build the most sensitive detector of energy exchanged between the quantum system and its environment? Ultrasensitive calorimetry is currently under intensive study, and it can eventually become the microscope of quantum dynamics on the level of exchange of energy by individual quanta emitted or absorbed by the quantum system. This would give us the optimal tool to investigate, *e.g.* the said stochastic thermodynamics in true quantum regime. Many other fundamentally and practically important questions arise and can potentially be answered by cQTD: for instance, where is the “Heisenberg cut”, *i.e.* the boundary between the quantum system and the classical environment in a



▲ FIG 3: One of the central tools in quantum thermodynamics is a thermometer measuring the heat absorbed in a mesoscopic bath. Here we depict the idea of a calorimetric measurement due to a single absorption event. A qubit (X-shaped object on the left) relaxes to its ground state and emits a quantum of energy via the resonator in the middle to the absorber on the right, a tiny metal electrode (not in scale). The thermometer observes this energy in form of instantaneous temperature rise due to finite heat capacity C and subsequent decay. The noise in the trace arises from fundamental thermal fluctuations and depends on C and thermal conductance G_{th} of the absorber element [5]. (Figure by Bayan Karimi.)

realistic experiment? What happens when the couplings between sub-systems (inter-quantum system couplings, couplings to the heat baths) are tuned at will. Standard ways of treating open quantum systems are based on weak-coupling assumptions, where sub-systems can be identified and work and heat are definable: but once the coupling becomes sufficiently strong, such separation becomes meaningless, and one needs to revise the whole approach to the quantum thermodynamics problem. How does a quantum system thermalize, and does it find an equilibrium thermal state even in the absence of a heat bath?

With the tools at hand we are about to address many exciting fundamental physics questions at the crossroads of quantum mechanics and thermodynamics, and to build devices with unprecedented qualities and performance. ■

About the Author



Jukka Pekola is a professor of quantum nanophysics at Aalto University in Helsinki, and directs the national centre of excellence, Quantum Technology Finland. He investigates thermodynamics and control of heat in quantum circuits.

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CRYOGENIC DETECTORS

EXPLORING NEW PHENOMENA IN PHYSICS AND ASTROPHYSICS

■ Klaus Pretzl – Laboratory for High Energy Physics at the University of Bern, Switzerland – DOI: <https://doi.org/10.1051/epn/2021303>

The potential to measure small energy transfers with very high energy resolutions motivated the development of cryogenic detectors to search for dark matter in the universe, the neutrino mass, neutrinoless double beta decay, and new phenomena in astrophysics. Other fields like material and life sciences also benefited from these developments.

A typical cryogenic calorimeter consists of an absorber, a thermometer which measures the temperature increase due to the energy transfer of a particle in the absorber, and a thermal bath which restores the temperature of the absorber to its original base value. In contrast to other devices, cryogenic calorimeters measure the total deposited energy in form of ionization and heat (phonons). They can be made from different materials including superconductors, a feature which turns out to be very useful for many applications. Most detectors use superconducting materials since there are very low energy quanta involved. It only takes energies of the order of a meV to break a Cooper pair in a superconductor, as compared to a few eV which are needed to create an electron hole pair in a solid state device. Due to large quantum statistics, energy resolutions of typically a few eV for small energy transfers of a few keV can be achieved with most cryogenic detectors. This is more than an order of magnitude better than what can be reached with solid state devices. A drawback is that they have to operate at mK temperatures requiring complex refrigeration systems, and that they have limited rate capabilities (1Hz-1kHz).

Cryogenic detectors differ in the way they are converting the excitation energy in the calorimeter into a measurable signal. There are devices using phonon sensors, quasiparticle detection or magnetic thermometers. Excitations in the absorber produce electrons, photons (photoelectrons) and phonons, which degrade in time via electron-phonon and phonon-phonon interactions until the system reaches a thermal equilibrium. Calorimeters operating in the equilibrium mode deliver the best energy resolutions, but are intrinsically slow, providing

second to millisecond signals. In some applications they are also used in a non-equilibrium mode, which makes them faster (microsecond signals), but with inferior energy resolutions.

Phonon sensors

Semiconducting thermistors and superconducting transition edge sensors (TES) are used as resistive thermometers. They measure the change of a resistor as result of a temperature change in an absorber. Due to the long thermalisation and recovery time of the system they have slow response signals which limits their counting rate capability to a few Hz. They also have to deal with Joule heating which results from the power dissipation of the thermometer read out current into the system. However, for sensors connected to a voltage biased electrothermal feedback system the effect of Joule heating can be largely reduced. This feedback also stabilizes the operating temperature of the system in a self-calibrating mode. Other phonon sensors are magnetic thermometers with an inductive readout. They do not dissipate power into the system.

A thermistor is a heavily doped semiconductor below the metal insulator transition. Its conductivity results from a phonon driven electron-hopping mechanism between impurity sites. Good uniformity of doping concentrations has been achieved either with ion implantations or with neutron transmutation doping (NTD). With thermistors very high energy resolutions can be achieved. In addition, they are easy to handle and commercially available. This makes them very attractive for many applications.

A TES sensor consists of a superconducting strip or film attached to an absorber. It operates at a temperature

in the narrow transition region between the superconducting and the normal phase. The very steep resistance change versus temperature in the transition region provides a high sensitivity to very small energy transfers in the absorber. Superconducting TES sensors can be attached to absorbers made from different materials. But they can also be used as absorber and sensor at the same time. Superconducting TES detectors are also sensitive to non-thermal phonons (ballistic phonons) with energies larger than the binding energy of Cooper pairs. These phonons produce quasiparticles before they thermalize. Since this process is much faster than thermalization, it enhances the counting rate capability considerably, up to several kHz. The application of the abovementioned auto-biasing electro-thermal feedback system turns out to be very advantageous for the operation of large pixel detectors or calorimeter arrays. Superconducting TES sensors belong to the most advanced cryogenic detectors with many applications in numerous fields of research.

Magnetic sensors make use of the temperature dependence of magnetic properties of metallic materials. Sensitive magnetic calorimeters (so called metallic magnetic calorimeters, MMC) are made from paramagnetic strips in thermal contact to an absorber. They are placed in an external magnetic field. A temperature change in the absorber leads to a change in the magnetization of the sensor, which can be measured with a SQUID (superconducting quantum interference device) magnetometer.

Quasiparticle detection

External particle interactions in a superconductor lead to the breaking of Cooper pairs and quasi-particle production. The energy loss of the particle is proportional to the number of quasi-particles produced. It can be measured with a superconducting tunnel junction (STJ), more widely known as Josephson junction. When biasing the STJ at a suitable voltage, the tunnelling current is proportional to the excess number of quasi-particles produced. A typical STJ consists of two thin superconducting films separated by a very thin tunnel barrier, which is usually made from the oxide of one of the superconductors. In order to keep the tunnelling time shorter than the recombination time of the quasi-particles, the overlap region of the films (100×100 micrometer squared) and the resistance in the junction have to be ●●●



If the dark matter in the universe consists of weakly interacting particles (WIMPs), it can potentially be detected by measuring the nuclear recoil energy in elastic WIMP-nucleus scatterings. ⇨⇨

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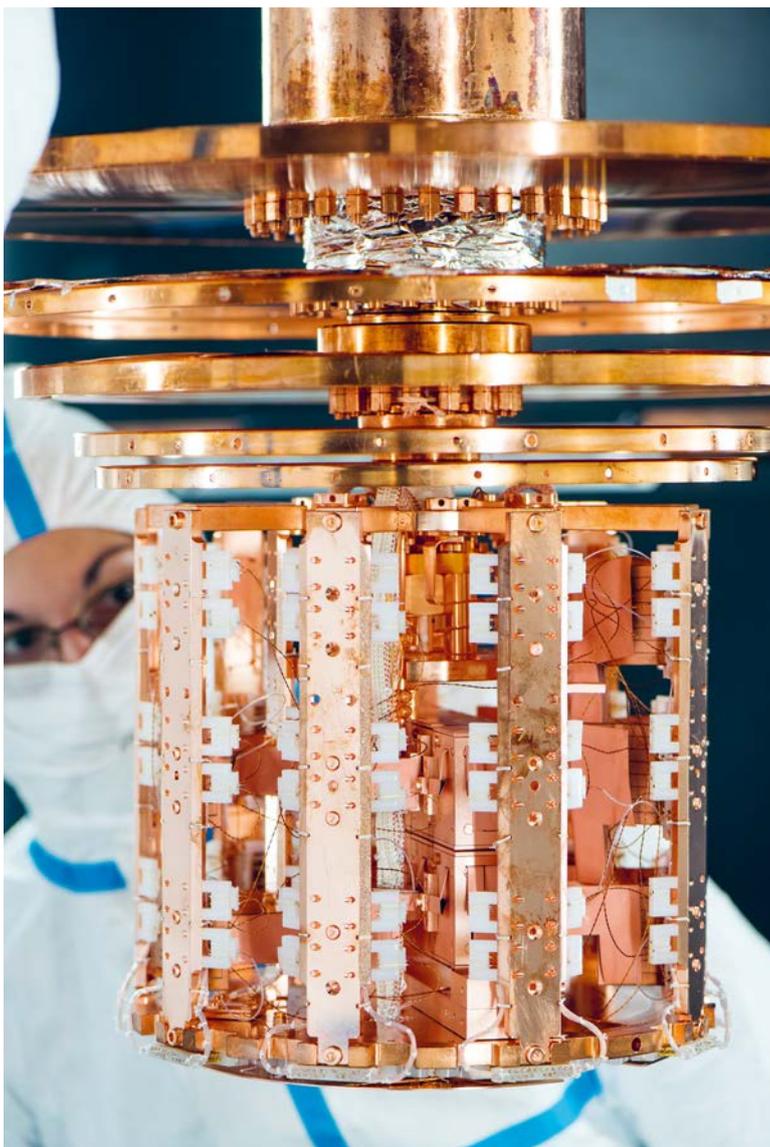
●●● kept very small. However, for very thin films the quantum efficiencies for X-ray detection are very low. This can be improved by choosing a larger size superconducting absorber as substrate to the STJ. Quasiparticles will be trapped in the junction when the absorber material has a higher energy gap with respect to the junction. STJ devices are frequently used as multi-pixel antennas in astrophysical observations.

Another attractive quasiparticle sensor is the microwave kinetic inductance detector (MKID). It consists of a thin superconducting film which is part of a transmission line resonator. MKID operates in a non-equilibrium mode. Quasi-particles produced by Cooper pair breaking of incident photons will change the inductive surface impedance of the superconductor and consequently the transmission phase of the resonator. The change of the transmission phase is proportional to the number of produced quasi-particles and thus to the energy of the incident photons. MKID allow simple multiplexing by coupling an array of many resonators with slightly different resonance frequencies to a common transmission

line. As a result, only one amplifier is required to treat the signals from a large number of detectors. This feature allows for a simple multiplexing of large readout systems. MKID based detectors find many applications in multipixel X-ray and single photon cameras.

An early development of cryogenic detectors have been superheated superconducting granules (SSG). A SSG detector consists of millions of small size grains with a typical diameter of 30 micrometer diluted in a dielectric material and embedded in an external magnetic field. The grains are made from superconducting materials of type-1 (Sn, Al, Pb,...) and can be produced industrially. SSG acts as absorber and detector at the same time. An energy transfer in a single grain can lead to the transition of the grain from a metastable superconducting to a normal conducting state due to the disappearance of the Ochsenfeld-Meissner effect. Transitions of a single grain in a very large sample are detected by a conventional pick-up coil or a SQUID magnetometer. Primarily used as a threshold detector, it has so far found limited applications. Nevertheless, it was successfully employed in a neutron scattering experiment and in an early dark matter search.

▼ FIG. 1:
A module of the cryogenic dark matter detector of the CRESST experiment in the Gran Sasso Underground Laboratory in Italy (Photo credit: T. Dettlaff, Max-Planck-Institut für Physik, München). © T.Dettlaff, Max Planck Institut für Physik in München.



Applications

If the dark matter in the universe consists of weakly interacting particles (WIMPs), it can potentially be detected by measuring the nuclear recoil energy in elastic WIMP-nucleus scatterings. Dark matter searches are in an advanced stage requiring more and more massive detectors to increase their sensitivity. Cryogenic calorimeters have the potential to detect very small recoil energies and to use a very large variety of detector materials. Large recoil energies and high sensitivities can be achieved if the atomic mass to the detector is matched to the WIMP mass. Massive cryogenic calorimeters of several 10 kg are already in operation. They complement the even more massive (ton-range) liquid Xenon and liquid Argon calorimeters, which are already employed in deep underground dark matter experiments.

The discovery of neutrino oscillations by the Kamiokande experiment in Japan suggests that neutrinos are massive. Several experiments now focus on the questions: What is the absolute mass of the neutrinos, and are the neutrinos and their antiparticles different or identical particles (*i.e.* Dirac or Majorana type particles). An answer to the latter question can be searched for in the nuclear double beta decay, a process, which was suggested in 1935 by Maria Goeppert Mayer. This transition can occur in two ways, where either two electrons and two antineutrinos or only two electrons end up in the final state. An observation of a neutrinoless final state would imply that the neutrino cannot be distinguished from its antiparticle. In search for this transition, the double beta decay in Tellurium-130 was chosen because of its

high transition energy and isotopic abundance. Massive (1 ton) cryogenic detectors using Tellurium absorber crystals and Germanium NTD thermistors are under construction in order to surpass the presently reached sensitivities for this decay mode.

Direct neutrino mass experiments aim to measure the end point of the energy spectrum of electrons in beta-active nuclei with high precision. Spectroscopic measurements of the electrons often have to deal with final state interactions in the radioactive source. Cryogenic detectors circumvent these problems by measuring the total energy of the electrons including the final state interactions. The Rhenium-187 beta decay is a good candidate for this investigation since it has a low endpoint energy (2.6 keV) and a large isotopic abundance. Rhenium is also a superconductor and well suited as a cryogenic detector. Also the electron capture decay of Holmium-163 is being considered for such an investigation.

Astrophysics is a rapidly growing field requiring instruments with broadband capability, high spectral resolving power, efficient photon counting and large area imaging properties. Large pixel arrays of cryogenic detectors are already in use in many astronomical observatories. Because of their wide spectral sensitivity, they are more and more replacing conventional dispersive spectrometers. Cryogenic pixel arrays have also been employed to investigate the polarization of the cosmic microwave background radiation (CMB). These polarization measurements could provide revealing insight into the inflationary scenario of the early universe, signalling the effect of primordial gravity waves.

Present developments of cryogenic detectors are concentrating upon low mass dark matter particle (below $1\text{ GeV}/c^2$) and coherent neutrino scattering searches as well as upon the technical realization of large pixel arrays for astrophysics observations and the multiplexing of large electronic readout systems. A more detailed description of cryogenic detectors and their applications can be found in Refs. 1 and 2, and in the references therein. ■

About the author



Klaus Pretzl is Professor emeritus of Experimental Physics at the Laboratory for High Energy Physics at the University of Bern. He has also been actively involved in the development of cryogenic detectors.

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CRYOGENIC DARK MATTER SEARCHES

■ **Laura Baudis** – Physik-Institut, University of Zurich, laura.baudis@uzh.ch – DOI: <https://doi.org/10.1051/epr/2021304>

In the decades-old quest to uncover the nature of the enigmatic dark matter, cryogenic detectors have reached unprecedented sensitivities. Searching for tiny signals from dark matter particles scattering in materials cooled down to low temperatures, these experiments look out into space from deep underground. Their ambitious goal is to discover non-gravitational interactions of dark matter and to scan the allowed parameter space until interactions from solar and cosmic neutrinos are poised to take over.

▲ Installation of the top photosensor array of the XENONnT experiment in a cleanroom at the Gran Sasso Underground Laboratory. Photo credit: the XENON collaboration)

The matter density in the Universe has been on the minds of cosmologists for over a hundred years, for it determines its geometry and expansion rate. Another intriguing question is its composition: only 15% is made of baryons, the matter of stars and stellar remnants, of interstellar and intergalactic gas. This component can emit or absorb radiation from the radio, infrared, visible, ultraviolet to the X-ray and gamma range of the electromagnetic spectrum, and

thus be observed with ground- or space-based telescopes. For almost a century we know however that the majority of matter is non-baryonic: it does not emit, absorb or scatter light, and so far has only been observed through its gravitational influence on luminous matter [1]. One of the major open questions is this: What is the composition of dark matter? Is it made of new elementary particles or primordial black holes, or perhaps both, is it one species of particles or many? While we can chart the

distribution of dark matter from galaxies to the largest observed structures and measure its density in the early Universe and today, we are in complete darkness when it comes to the essential question: What is it and how does it interact with visible matter?

Dark Matter and its Distribution in the Milky Way

Conjectures about the nature of dark matter span more than eighty orders of magnitude in mass — from ultra-light, or wave-like dark matter with a mass of 10^{-22} eV/ c^2 to primordial black holes with up to tens of solar masses — and many orders of magnitude in interaction strengths with baryonic matter. While no particle of the Standard Model is a good candidate, any contender must be consistent with a vast range of astrophysical and cosmological observations, while also satisfying constraints from laboratory searches [2]. The question on the nature of dark matter is intrinsically connected to the physics of the energetic, early Universe, when a dark species could have been produced together with neutrinos, electrons, quarks, photons and other known particles¹. This dark species provided the extra gravitational force, allowing structures to form from initial, small irregularities due to quantum fluctuations, and in particular lead to the formation of spiral galaxies like our own. Some of the most appealing candidates are axions, with masses at the $\mu\text{eV}/c^2$ scale, and weakly interacting massive particles (WIMPs), with masses from a few GeV/c^2 (where the mass of the proton is about $1 \text{ GeV}/c^2$) to $\sim 100 \text{ TeV}/c^2$.

The luminous structure of the Milky Way thus resides in an extended, roughly spherical dark matter halo with radius of $\sim 100 \text{ kpc}$ (an order of magnitude beyond the baryonic disk), implying a total mass of $\sim 10^{12}$ solar masses. From the measured galactic rotation curve and the kinematics of stars as tracers for the dark matter and hence the underlying gravitational potential, one can derive the density and velocity of dark matter. At the solar system's location, 8 kpc away from the Galactic Centre, the dark matter density is around $0.3 \text{ GeV}/\text{cm}^3$ (or equivalently, $0.008 \text{ solar masses}/\text{pc}^3$), while the average speed is $\sim 200 \text{ km/s}$ [3].

Direct detection experiments in silent locations

One of the main laboratory probes of dark matter in the Milky Way is called direct detection. Experimentalists aim to record those ultra-rare occasions when an invisible particle scatters in a target material. As we move, together with the Sun, around the Galactic Centre and through the dark halo, we encounter a wind of dark matter particles. Their density and velocity distribution, together with their mass and interaction strengths, determine the expected scattering rates in a detector, as well as the

deposited energies. The latter are tiny, at the keV-scale and below, while from the fact that we haven't seen any convincing signal in a direct detection experiment so far, the rates are smaller than one per kilogram or tonne of target material and year for masses below and above a few GeV/c^2 , respectively. These are almost unthinkable low rates, millions of times below those expected from cosmic ray interactions at the Earth's surface, requiring that detectors are operated in deep underground laboratories. An underground location is far from sufficient. The experiments must also be placed in extremely quiet environments: shielded from the natural radioactivity of their immediate surroundings, and purified from potential nuclides which can emit alpha, beta and gamma radiation when they decay inside the target material and possibly mimic the expected signal. After about three decades of development, two technologies are reaching unprecedented sensitivities in the search for dark matter interactions: ultra-pure, liquified noble gas detectors using liquid argon and xenon, and crystals operated only a few tens of degrees above the absolute zero [4].

Liquified noble gas detectors

From all noble elements, only argon and xenon are currently employed as targets for dark matter detection, while R&D on helium is ongoing. In their liquid phase, argon (at $T \sim 87 \text{ K}$) and xenon (at $T \sim 165 \text{ K}$) are outstanding media for building large, homogeneous, compact and self-shielding detectors which can reach ultra-low backgrounds at their cores. Both liquid argon and xenon are excellent scintillators and good ionisers in response to the passage of radiation. The simultaneous detection of light (in the VUV-region at 128 nm and 175 nm respectively) and charge leads to a good energy resolution and the identification of the primary particle interacting in the liquid, an essential feature for picking out a signal-like interaction from background. In addition, the three-dimensional mapping of the spatial position of scatters in time projection chambers (TPCs) allows to select single-events — as expected from dark matter particles — from multiple interactions in the detector. One of the challenges in noble liquids is their purification from radioactive isotopes which are either present in the atmosphere (^{39}Ar , ^{85}Kr) or emanated by detector materials (^{222}Rn) and, mixed with the liquid, lead to backgrounds due to beta- and alpha-radiation. Depletion by isotopic separation in large-scale cryogenic distillation columns, and by extraction from underground wells, in case of argon, have lead to concentrations within about a factor of ten from those needed to reduce these contributions below those from elastic scatters of solar ●●●

¹ Primordial black holes are thought to originate from gravitational collapse of large density fluctuations in the early Universe



▲ FIG. 1: The top photosensor array of the XENONnT dark matter detector. With 8.6 tons of liquid xenon in total, the experiment will start a first science run at the Gran Sasso Underground Laboratory in Italy in spring 2021 (Photo credit: the XENON collaboration).

●●● pp-neutrinos with electrons. A previous generation of argon and xenon TPCs (DarkSide-50, LUX, PandaX-II, XENON1T) has probed a large part of the theoretical parameter space for particles with masses above a few GeV/c^2 , reaching interaction cross sections on nucleons as low as 10^{-47} cm^2 at $30 \text{ GeV}/c^2$. To set this into perspective, the cross section of neutrinos generated in beta-decays, thus with energies around 1 MeV, is $\sim 10^{-44} \text{ cm}^2$. Experiments to acquire data in the next few years or currently in construction, with multi-tons of noble liquids as dark matter target (LUX-ZEPLIN, XENONnT, PandaX-4T, DarkSide-20k) and in planning (DARWIN, ARGO) will have a fair chance to unveil first, feeble signs of dark matter interactions [5]. Once such a direct evidence for a signal has been established, the focus will shift towards measuring the properties of the dark species, such as their mass, interaction cross section and possibly spin.

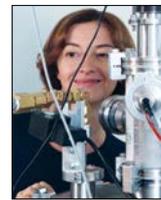
Crystals at mK temperatures

The development of cryogenic experiments operated at sub-Kelvin temperatures has been driven by the exciting possibility to perform a calorimetric measurement down to very low energies, with unsurpassed energy resolution. Because of the T^3 -dependence of the heat capacity of a dielectric crystal, at low temperatures a small energy deposition can significantly change the temperature of the absorber. As an example, at a temperature of 10 mK, a 1 keV energy deposition in a 100 g detector increases its temperature by about 1 μK . This change in temperature is measured either after the phonons reach equilibrium, or thermalise (e.g., with neutron transmutation doped sensors), or when they are still out of equilibrium, or athermal (e.g., with transition edge or kinetic inductance sensors), the latter also providing information about the location of an interaction in the crystal. Dark matter detectors based on the bolometric technique also read out ionisation in semiconductors (EDELWEISS, with Ge

crystals, and SuperCDMS, with Ge and Si crystals) or the scintillation light in a transparent crystal (CRESST, with CaWO_3 crystals), since the ratio of the two signals allows to differentiate between different type of interactions. Recently, these experiments were optimised for light dark matter searches, with sub- GeV/c^2 masses. One avenue is to operate the detectors at higher bias voltages and to amplify the phonon signals produced by drifting charges, exploiting the Neganov-Trofimov-Luke effect. As an example, an energy threshold of 56 eV was reached by SuperCDMS for a bias voltage of 70 V across a 600 g Ge crystal. Another direction is to decrease the size of the crystals, as followed by CRESST, where energy thresholds around 100 eV were achieved with 24 g CaWO_3 crystals. Some of the challenges of future bolometric dark matter detectors are to increase the surface area coverage of phonon sensors, the fabrication of transition edge sensors with lower operational temperatures to further decrease the noise and thus energy thresholds, as well as background control. New purification and in-house crystal growth techniques are developed, and underground crystal growth and detector development to avoid activation by cosmic rays are considered [5].

Outlook

We live in a vast sea of dark matter, but its composition at the fundamental level remains an enigma. Cryogenic experiments based on liquefied noble gases and crystals operated at a few tens of degrees above the absolute zero have demonstrated the highest sensitivities to feeble and ultra-rare scatters for a wide range of dark matter particles. While the pragmatic goal is to probe the theoretically allowed parameter space until interactions from cosmic neutrinos will take over, these experiments might well herald one of the greatest discoveries in twenty-first century physics. ■

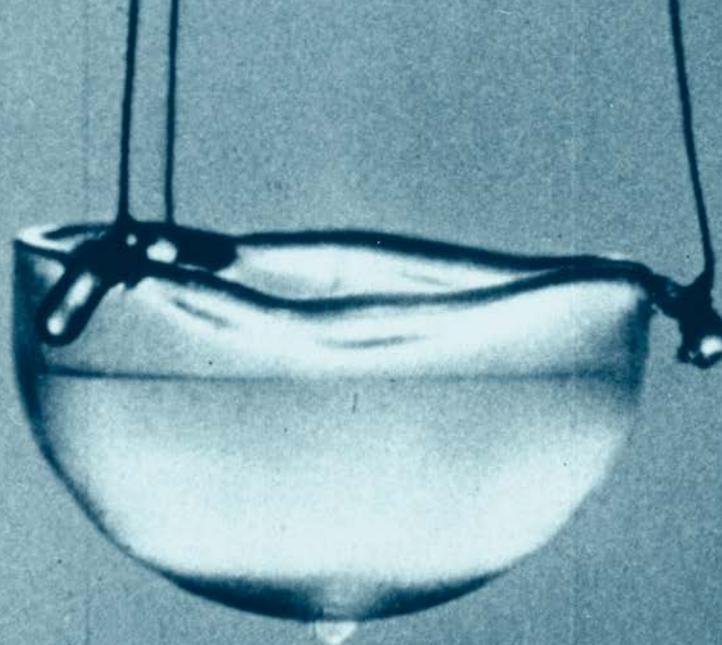


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Laura Baudis is a professor in the Physics Department of the University of Zurich. She has a long interest in dark matter and neutrino physics and has worked with cryogenic detectors since her days as a PhD student in Heidelberg. She is one of the founders of the XENON programme and leads the DARWIN collaboration with the aim to build an observatory based on a 40 t liquid xenon time projection chamber.

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QUANTUM STORM IN A COLD CUP

Quantum turbulence, which manifests itself via a tangle of quantized vortices, occurs in quantum fluids, whose properties depend on quantum physics rather than classical physics. Here we report on two limiting forms of quantum turbulence which have been identified and how two-dimensional turbulence, until recently a mathematical idealization, has become experimental reality.

■ **Carlo F. Barenghi¹ and Ladislav Skrbek²** – DOI: <https://doi.org/10.1051/ePN/2021305>

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It was the Renaissance genius Leonardo da Vinci, an acute observer of Nature, who first noticed that turbulence consists of eddies (or swirls, or vortices) of different sizes and strengths, which he sketched in a famous drawing. This insight was not followed up on until the late 1800's, when Osborne Reynolds reached the same conclusion and brought it to the attention of physicists.

Despite the great progress since the times of Reynolds, turbulence is still a challenge: it is a multi-scale nonlinear phenomenon in which billions of degrees of freedom are excited simultaneously and interact with each other. To complicate this statistical problem, the turbulent velocity field fluctuates wildly both in time and from point to point - it is essentially non-differentiable. Even

the mathematical nature of the solutions of the governing equation of motion, the Navier-Stokes equation, has been questioned. In the year 2000, it was selected by the Clay Mathematics Institute as one of the seven Millennium Problems whose solution is worth a prize of one million dollars each (to date, only one of the seven problems – the Poincaré conjecture - has been solved).

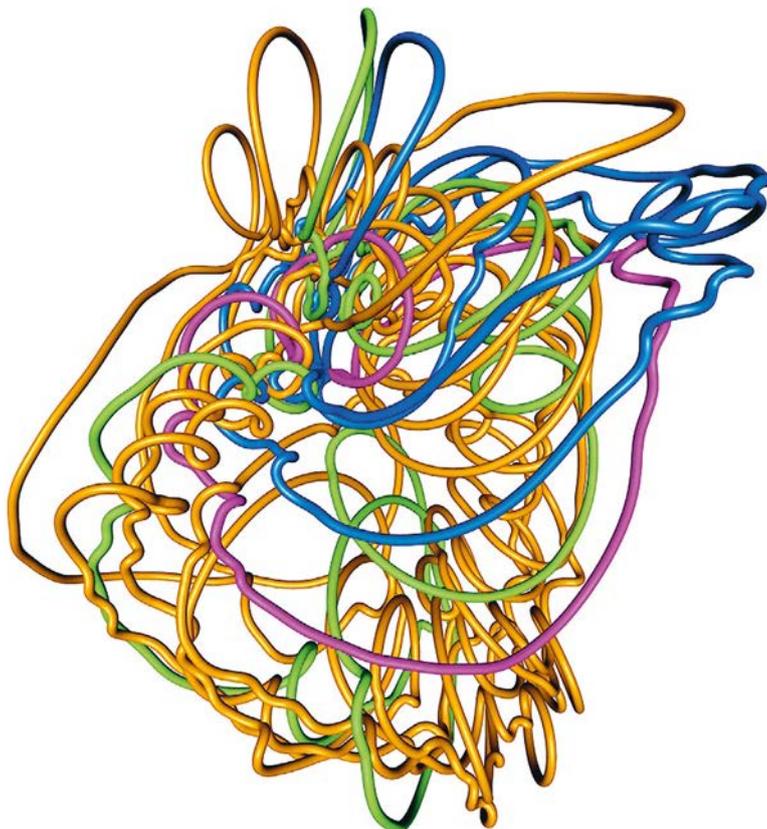
More recently, a new aspect of the turbulence problem has emerged: turbulence in quantum fluids, or quantum turbulence (QT) [1]. Key properties of quantum fluids depend on quantum physics rather than classical Newtonian physics, something which typically requires very low temperatures (lower than some critical temperature of the system). There are many quantum fluids, but here we ●●●

▲ A very cold cup of superfluid ⁴He, at temperature less than 2.2 Kelvin, where liquid ⁴He represents a quantum fluid of extraordinary physical properties that depend on quantum rather than classical physics.

••• consider ^4He , ^3He and atomic Bose-Einstein condensates (BECs) - small clouds of ultra-cold gases confined by magneto-optical traps at temperatures of order Kelvin, milliKelvin and microKelvin, respectively.

The first important property of these quantum fluids is superfluidity (or absence of viscosity, so named in analogy to superconductivity), which is the ability to flow, under some conditions, without any friction. Superfluidity is a consequence of the shape of the dispersion relation between energy and momentum of elementary excitations: unless an object moves faster than a critical velocity, it cannot lose energy to the fluid, which thus appears to the moving object as a background vacuum. The second important property is that in the zero temperature limit the entire fluid is described by a macroscopic complex wavefunction Ψ . At non-zero temperature there is also a thermal fraction (called the normal fluid in helium to distinguish it from the superfluid component) which behaves like an ordinary viscous fluid. The uniqueness of Ψ and the basic rules of quantum mechanics imply that vorticity is constrained to thin cores of quantized vortices - vortex lines - of fixed strength: the quantum of circulation $\kappa=h/m$ where h is the Planck constant and m the mass of the relevant boson (such as the ^4He atom or a Cooper pair of ^3He atoms). The vortex axis, where Ψ is suppressed, is a topological line defect (the phase is undefined), surrounded by a thin tubular region of depleted density, in the case of ^4He of tiny radius $a_0 \approx 10^{-10}$ m. This property is in sharp contrast to what happens in ordinary viscous fluids, where vorticity is unconstrained in both shape and strength.

▼ FIG. 1: Snapshot of a small numerically computed tangle of vortex lines in ^4He . The vortex lines are represented as thick coloured tubes to visualize the 3D nature of QT (in reality, the vortex cores are about 10,000 times thinner than the average distance between the vortex lines). Note the helical deformations of the vortex lines (Kelvin waves) and the highly knotted topology of QT [2].



Classical turbulence

In order to capture the general features of ordinary (classical) three-dimensional (3D) turbulence in viscous fluids, physicists invented the concept of homogeneous isotropic turbulence (HIT), a state which is independent of position and orientation. An example of HIT is the turbulent flow inside a wind tunnel of width D after subtracting the mean velocity. A statistically steady state of HIT is sustained by continuous energy input at rate ϵ at some large scale $M < D$, where D is the system size (for example, M is the mesh size of the grid of the wind tunnel). This input compensates the losses $dE/dt = -\epsilon$ of turbulent kinetic energy E due to the fluid's kinematic viscosity, ν . Nonlinearity ensures that the injected energy is shifted without losses to smaller and smaller length scales (a mechanism called the Richardson energy cascade) until it reaches a dissipation length scale η (called the Kolmogorov length scale) which is small enough that kinetic energy is turned into heat. Simple dimensional analysis yields $\eta = (\nu/\epsilon)^{3/4}$. An inertial range of scales develops between M and η where viscosity does not matter and the distribution of the kinetic energy among eddies is proportional to the $5/3$ power of the eddies' size (Kolmogorov's law), neglecting for simplicity fine details known as intermittency corrections.

Quantum turbulence

QT can be easily excited in superfluid ^4He , in the B-phase of ^3He and in atomic BECs. Let us consider temperatures so low that the normal component is effectively absent. QT is then a disordered tangle of vortex lines (Fig. 1) - which move each other and reconnect when they collide. Since there is no viscosity, there is no dissipation scale η . However, as an analogy with classical fluids, one can define a quantum length scale, ℓ_Q , by replacing ν with the quantum of circulation, κ [3]. At scales larger than ℓ_Q , a small polarisation of vortex lines allows the stretching required to sustain the classical Richardson cascade. Indeed, at these scales experiments and numerical simulations display the same Kolmogorov distribution of kinetic energy among scales as observed in classical turbulence. At scales smaller than ℓ_Q there is no polarisation and the quantisation of circulation prevents stretching - individual vortex lines cannot stretch: at these scales, QT is unlike classical turbulence. Consistently, the velocity statistics are nearly Gaussian as in classical turbulence if probed at length scales larger than ℓ_Q but become power-laws if probed at scales smaller than ℓ_Q [4, 5].

The classical Richardson energy cascade cannot proceed beyond ℓ_Q but a non-linear transfer of energy further downscale is still possible along individual vortex lines. Fig. 1 shows that vortex lines sustain Kelvin waves, similar to those of a garden hose. The nonlinear interaction of Kelvin waves creates shorter and shorter waves in

a second cascade process with no classical analogy called the Kelvin wave cascade, until kinetic energy is eventually dissipated, either by phonon emission (in ^4He) or by exciting bound states in the vortex cores (in $^3\text{He-B}$). In other words, in both classical and quantum turbulence, the final destiny of the energy input at large scale M is the same: heat.

The emergence of the quantum scale in QT (its existence is a purely quantum effect, it vanishes in the quasi-classical limit of zero Planck constant), besides M and η , adds a twist to the story. If ℓ_Q is larger or similar to M , the vortex lines remain at random with respect to each other without forming any partial polarization, hence there is neither Richardson cascade nor inertial range. This regime of QT, identified in superfluid helium, phase transitions and atomic BECs, is called Vinen turbulence; its fingerprint is the temporal decay of the vortex line length which behaves as $L \approx 1/t$ for late times, unlike the $L \approx 1/t^{3/2}$ of Kolmogorov turbulence [3].

At non-zero temperatures, quantum fluids behave as two-fluid systems consisting of an inviscid superfluid and a thermal viscous component which introduces friction on the motion of vortex lines. In atomic BECs the mean free path of the thermal component is large, while in ^4He above 1 K it is short enough to behave like a classical Navier-Stokes fluid (the normal fluid) which may easily become turbulent, too. This opens new scenarios and a rich variety of turbulent flow regimes which are being investigated. Moreover, in some quantum flows (such as in thermal counterflow of ^4He , important for cryogenic engineering applications), QT can be simultaneously driven on large and small scales. A recent review [3] provides a general phenomenological understanding of rich variety of turbulent quantum flows of superfluid helium.

While the properties of helium are fixed by the temperature and pressure of an experiment, physical properties of atomic BECs (the sign and strength of the inter-atomic interaction, the density, shape, size and even the dimensionality of the system) can be tuned by the experimentalists. Unfortunately atomic condensates seldom contain more than $\approx 10^6$ atoms, hence they are relatively small: the ratio D/a_0 , representing the number of linear degrees of freedom, is typically only 10-20, which must be compared to the staggering $D/a_0 \approx 10^{10}$ achieved with ^4He . Despite the small size of atomic BECs, there is experimental evidence for the emergence of scaling laws [6]. Atomic BECs are thus ideal settings to study the crossover from chaos to turbulence.

Two-dimensional quantum turbulence

Atomic BECs that are so tightly confined in one direction that their thickness is of the order of a_0 are essentially 2D systems. Given the same number of atoms, the ratio D/a_0 (hence the number of possible vortex lines in the systems) can be made much larger than in 3D. BECs thus

offer the opportunity of studying truly 2D turbulence, something which until recently was considered a mathematical idealization.

In 2D turbulence there is an inverse energy cascade from small to large-length scales (contrasting the 3D Richardson cascade in the other direction), hence the formation of large coherent vortex structures like Jupiter's Red Spot. In terms of discrete vortices, this effect is captured by Onsager's idea of the 2D vortex gas. In a confined system (such as an atomic BEC), the number of accessible states is not a monotonically increasing function of the energy, but reaches a maximum before decreasing. This property implies that at a high enough energy the temperature becomes formally negative; vortices of the same sign merge, creating large clusters of positive and negative vorticity, as already demonstrated in the laboratory [7].

Conclusions

Turbulence is a traditional interest of fluid dynamicians, engineers, geophysicists and astrophysicists. This is changing. Novel forms of turbulent quantum flows are being explored, emerging in helium superfluids, single and two-component atomic condensates, polaritons, spinor condensates, quantum ferrofluids and models of the early Universe. Quantum turbulence, demonstrating the universality of concepts such as energy cascades and reconnections, represents a fast-growing branch of physics. ■

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NOBLE LIQUID CALORIMETRY AT THE LHC AND PROSPECTS OF ITS APPLICATION IN FUTURE COLLIDER EXPERIMENTS

■ Martin Aleksa – EP Department, CERN, Geneva – DOI: <https://doi.org/10.1051/epr/2021306>

Calorimetry is an important measurement technique in experimental particle physics. Although calorimeters based on liquefied noble gases were first proposed 50 years ago, they continue to play an important role in modern particle physics and have substantially contributed to the discovery of the Higgs boson at the Large Hadron Collider (LHC) at CERN in 2012.



Calorimetry refers to the absorption of a particle and the transformation of its energy into a measurable signal related to the energy of the particle [1]. A calorimetric measurement requires that the particle is completely absorbed and is thus no longer available for subsequent measurements. Since the energy of the incident particle is usually much higher than the threshold of inelastic reactions between the particle and the detector medium, the energy loss will produce a cascade of lower energy particles, whose number is proportional to the incident energy. Charged particles in the shower ultimately lose their energy through elementary processes, mainly by ionization and atomic level excitation.

Electromagnetic calorimeters

In electromagnetic calorimeters, specialized in the measurement of photons and electrons, the shower development is characterised by the radiation length X_0 which is defined as the mean distance in which electrons lose all but $1/e$ of their initial energy by radiation.

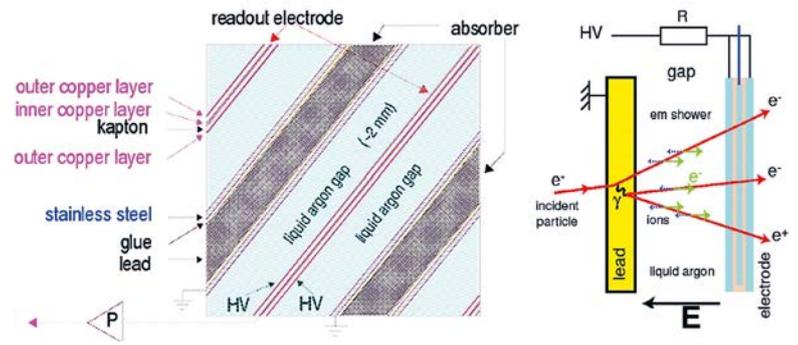
To fit into limited space, electromagnetic calorimeters need to be made of dense materials with a short radiation length. Sufficient longitudinal shower containment for typical particle energies requires a depth of above $20 X_0$. This can be achieved either by homogeneous calorimeters, usually consisting of very dense scintillating crystals (e.g. PbWO_4 , $X_0 = 8.9$ mm, LYSO, CsI, ...) or sampling calorimeters in which high-Z absorbers (e.g. Pb, $X_0 = 5.6$ mm or W, $X_0 = 3.5$ mm) are stacked with active medium and electrodes interleaved. The left picture of Figure 1 illustrates this principle. Compared to homogeneous calorimeters consisting exclusively of active medium, sampling calorimeters usually exhibit worse energy resolution, since only a statistically fluctuating fraction of the shower leads to energy deposits in the active medium.

Calorimeters using liquefied noble gases (noble liquids) are based on the measurement of the ionization charge produced inside the liquid. As shown in the right sketch of figure 1, the charges move in an applied electric field, inducing a current in readout electrodes proportional to the liberated charge and hence to the energy deposited by the showering particle.

Noble liquid calorimetry

This technique was introduced in the early 1970s [2] using liquefied argon (LAr) as the active material. Other suitable materials are the heavier noble liquids (LKr, LXe), however, due to their much higher price and limited availability, they are less popular for large calorimeter systems in collider experiments.

Noble liquid ionization calorimeters offer a number of attractive advantages, especially for collider experiments. They are characterized by intrinsic stability and excellent



uniformity of response, adaptability to high segmentation, radiation hardness and reasonable cost. Indeed, the price of a litre of LAr compares favorably with the price of a bottle of beer. A disadvantage is the operation at cryogenic temperatures that requires cryostats and elaborate cryogenic systems.

The ATLAS experiment at the LHC

The LHC, the world's largest particle accelerator located at CERN, accelerates and collides protons at four interaction points with center-of-mass energies of 13 TeV. In these collisions, new particles are produced, most of which decay instantaneously into more stable particles. Figure 2 shows a transverse cross-section of one wedge of the ATLAS detector [3] consisting of many layers of particle detectors which are arranged cylindrically around the beam axis and the interaction point. All measurements combined contribute to the reconstruction of the full event, including short-lived particles which are created in the collision but decay instantaneously.

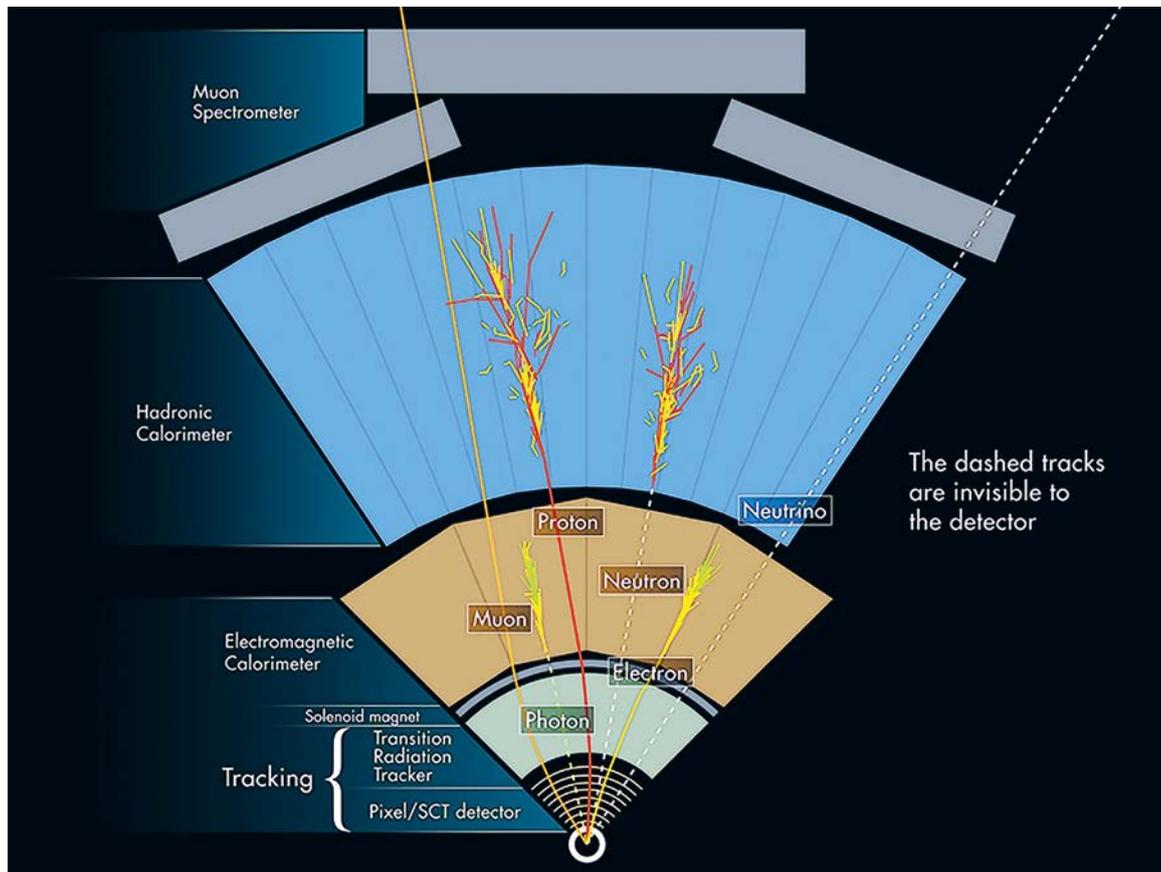
Electrons and photons shower in the electromagnetic LAr calorimeter, whereas hadrons produce more penetrating showers and are absorbed inside the hadronic calorimeter.

The ATLAS LAr electromagnetic calorimeter and its role in the discovery of the Higgs boson

The ATLAS electromagnetic calorimeter is a lead-LAr sampling calorimeter with accordion geometry [4] enabling a uniform acceptance without any gaps for services. The width of the active LAr gaps (Figure 1) is 2 mm in the central region, with a drift field of 10 kV/cm. The energy resolution of this calorimeter is $\sigma_E/E \approx 1.5\%$ for typical photon energies from Higgs decays. As shown in Figure 3, the calorimeter is segmented into four longitudinal read-out layers. The strip layer is finely segmented to distinguish between photons and neutral pions (π^0) decaying into two nearby photons. The photon pointing measurement aligns the measurements from the first and the second layer and extrapolates the photon trajectory to the interaction region. Such additional information obtained due to segmentation played a decisive role in the Higgs boson discovery.

▲ FIG. 1: Left: Stack of absorbers, electrodes and LAr gaps as realized in a typical sampling calorimeter (ATLAS LAr calorimeter, see below) Right: Ionization charges produced by charged particles traversing a LAr gap.

◀ Photo of the ATLAS barrel calorimeter and inner tracker. The LAr electromagnetic calorimeter is located in the aluminum cryostat visible inside the gold-colored front-end crates.

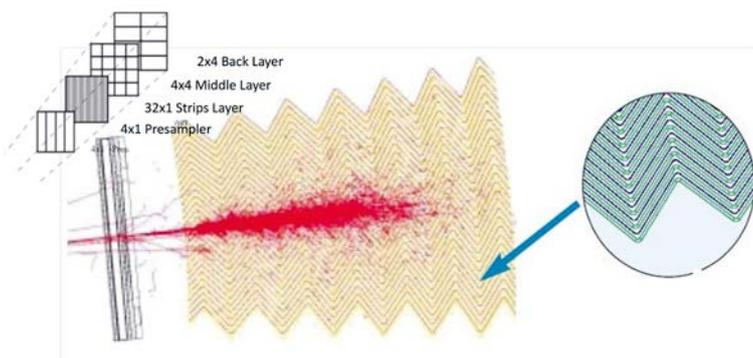


► FIG. 2: Different particles produced during collisions or the subsequent decays are measured in different layers of the detector.

Already during the design of the LHC detectors, the Higgs decay into a pair of photons was considered to be one of the most promising signatures, and was chosen as a benchmark for the optimization of the LHC detectors, especially the electromagnetic calorimeters.

In July 2012, the discovery of the Higgs boson in the ATLAS and CMS experiments was indeed driven by the high significance of the two-photon decay [5,6]. The two detectors use complementary concepts of their electromagnetic calorimeters: instead of a sampling calorimeter, CMS opted for a homogeneous lead tungstate crystal calorimeter ($PbWO_4$) providing excellent energy resolution. The crystal calorimeter of CMS outperforms ATLAS in the photon energy resolution, whereas the segmented ATLAS

▼ FIG. 3: Sketch of the shower development of an electron inside the ATLAS LAr accordion calorimeter.



¹ Particle flow optimizes the jet energy resolution by reconstructing each particle individually and by using the best measurement for each; charged particles measured in the tracker, photons and π^0 in the electromagnetic calorimeter, neutrons in the hadronic calorimeter.

LAr calorimeter compensates the worse resolution by photon pointing which helps to determine the correct primary vertex, crucial to calculate the transverse momentum and hence the invariant mass of the Higgs boson.

Noble liquid calorimetry in future collider experiments

The Future Circular Collider (FCC) is an ambitious project for an accelerator complex at CERN in the post-LHC era. An electron-positron collider, FCC-ee [7], is considered as a possible first step to measure precisely the Higgs properties and improve the measurement of key electro-weak parameters by several orders of magnitude. The tunnel length of 100 km is chosen to later house a 100 TeV hadron circular collider, the FCC-hh [8].

FCC-ee

The intrinsic stability, uniformity, excellent linearity and energy resolution as well as its adaptability to high segmentation make noble liquid calorimeters a promising candidate for the next generation of lepton collider or “Higgs Factory” experiments. At the FCC-ee [7] Standard Model precision measurements at the Z pole will benefit from statistical uncertainties up to 300 times smaller than at LEP. Also, precision measurements of the Higgs properties will have to rely on an extremely well controlled systematic error which requires an excellent understanding of the detector and the event reconstruction. High-resolution calorimetry and an efficient particle-flow¹ combination with the tracker measurement will be a prerequisite to achieve these ambitious physics goals.

FCC-hh

Experiments at the FCC-hh with unprecedented luminosity will face an extreme radiation environment, where radiation-hard noble liquid calorimetry seems to be the most adapted, and possibly the only applicable technology. Up to 1000 simultaneous collisions will occur every 25 ns at the interaction points, producing extreme pile-up conditions potentially hiding interesting collisions of high momentum transfer. High segmentation of the electromagnetic calorimeter is a prerequisite to distinguish energy deposits from interesting collisions and to reject pile-up. It has been shown that noble-liquid calorimetry can be optimized in terms of segmentation to allow for 4D imaging, machine learning and – in combination with the tracker measurements – particle-flow reconstruction [9]. These techniques, together with excellent timing resolution, will be essential to reconstruct jets, reject pile-up and identify the proton collisions of interest. ■

About the Author



A native of Austria, **Martin Aleksa** is a senior physicist at CERN. He is a member of the ATLAS collaboration since the late 90's and contributed significantly to the design, construction,

operation and data analysis of the experiment. He led the ATLAS LAr calorimeter collaboration for several years. Recently he started to work on ATLAS HL-LHC upgrades and on the conceptual design of an FCC experiment with focus on calorimetry.

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by Hans Peter Beck

President of the Swiss Physical Society – DOI: <https://doi.org/10.1051/epn/2021307>

Is there new physics around the corner?

New results from the LHCb collaboration at CERN and the muon g-2 collaboration at Fermilab have made headlines in recent weeks, not only in scientific journals but also in daily newspapers around the world, dubbing the standard model of particle physics getting cold feet or being at the end of the line. All lurid headlines aside, these new results make it clear that something new may be on the horizon.

Discrepancies

The LHCb result is putting stress on lepton universality between electrons and muons in specific decays of B mesons, of which the decay rates of $B^+ \rightarrow K^+ e^+ e^-$ and of $B^+ \rightarrow K^+ \mu^+ \mu^-$ are found to disagree at the 3.1 sigma level with each other. The muon g-2 result is measuring a discrepancy at the 4.2 sigma level, where the measured value of the muon magnetic moment is off from its theoretically predicted value. Measuring the magnetic moment of electrons and comparing it with its theoretical prediction yields to the best tested result in physics, with more than 10 significant figures accuracy. Both discrepancies hint that muons and electrons behave differently, unexpectedly. Both these discrepancies are extremely tiny and it takes enormous effort to measure them.

Evidence for new physics?

Statistical fluctuations or a forgotten systematic effect may still be at the cause of these reported preliminary results. More data taking and more scrutiny is needed and will not lead to a final conclusion for another couple of years to come. Still, if both results could be confirmed, new particles would need to be added to the well-known quarks, leptons and bosons, where leptoquarks or supersymmetric particles are among the most promising candidates.

Historical analog

Changing from particle physics to gravity and changing time from now to the mid-19th century, another extremely tiny effect made history. Back then, measuring the perihelion of Mercury and how it shifts year after year has been done with great care over many decades. A shift that resulted to be off from its theoretical prediction

by the extremely minute amount of only 43 arc seconds per century. The calculation, based on Newtonian gravity, included the gravitational pull of the sun and of the known planets. Adding a new planet to our solar system was proposed to provide remedy to this minute discrepancy. This hypothesized planet was dubbed Vulcan with an orbit inside the orbit of Mercury and so close to the sun that no optical instrument would be capable of seeing it directly. This was the state around mid 1850 and it took almost 70 years to resolve. The name Vulcan will ring a bell to all fans of the Star Trek series and of Mr Spock, the most prominent Vulcanian. Gene Roddenberry, the author of the original series, must have known about Vulcan and decided using it in his plot back in 1964. Einstein presented his theory of general relativity in 1915/16 and revolutionized the understanding of gravity. Conceptual flaws of the otherwise extremely successful Newtonian description of gravity were removed and the perihelion shift of Mercury be understood precisely without the need of Vulcan. Gravity is no longer a mysterious action at a distance, but is emerging from space-time itself, no longer acting instantaneously but propagating at the speed of light. Still, Newtonian gravity is being used for almost all calculations in everyday life. We do so in full confidence, because with the realm of general relativity, we know why Newtonian gravity works so well, and also up to which extreme conditions it will provide useful results. Newtonian gravity is, this way, fully complete.

Future expectations

We do not yet know what the new results from the LHCb and the muon g-2 collaborations tell us and where these will lead us. Maybe the hypothesized leptoquarks will have the same fate as the hypothesized planet Vulcan that, based on new insights obtained, was no longer needed. It took 70 years then, only the future will tell, how long it will take now. What is however clear already today, is that the Standard Model of particle physics works extremely well and will continue to be working extremely well. However, we do not yet know up to which extreme conditions it can provide useful results. The results from LHCb and muon g-2 may be those capable of paving the way further. ■

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