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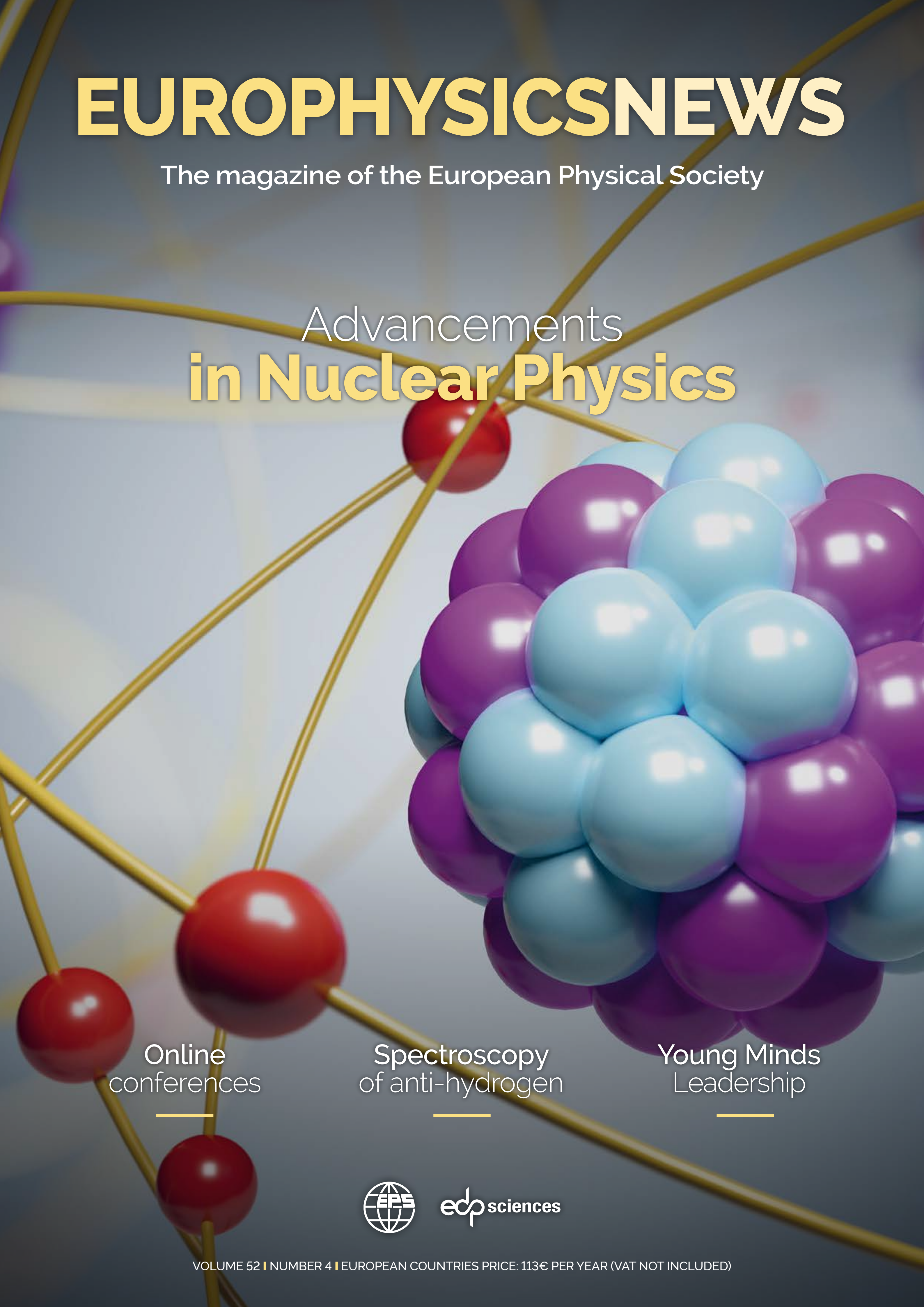
The magazine of the European Physical Society



Advancements in Nuclear Physics

Online conferences

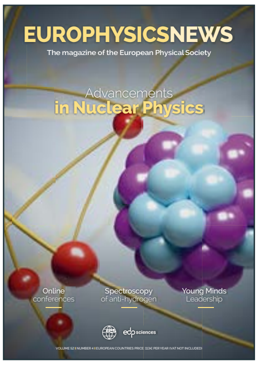
Spectroscopy of anti-hydrogen

Young Minds Leadership

EPS edp sciences

VOLUME 52 I NUMBER 4 I EUROPEAN COUNTRIES PRICE: 113€ PER YEAR (VAT NOT INCLUDED)

europhysicsnews



Cover picture: Traditional artist's impression of the nucleus of an atom. In this EPN issue advances in modern nuclear physics. © iStockPhoto.

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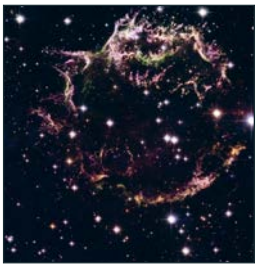
Online physics conferences



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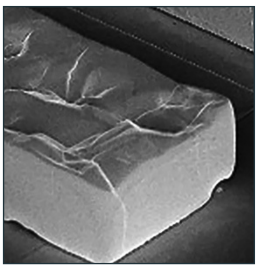
Rare isotope beams in astrophysics



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Breaking the millikelvin barrier

EPS EDITORIAL

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IN THE SPOTLIGHTS

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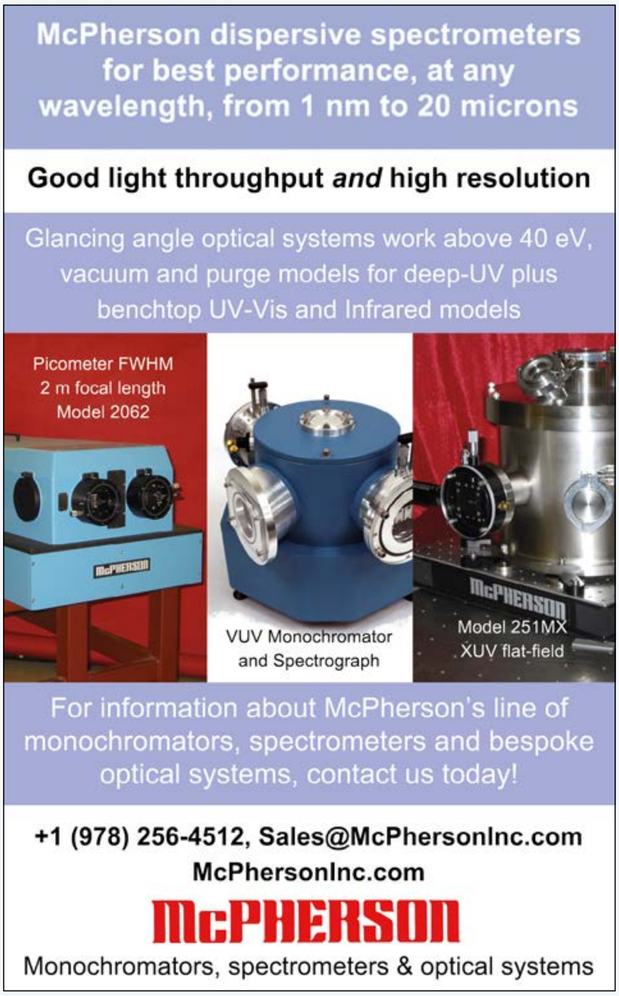
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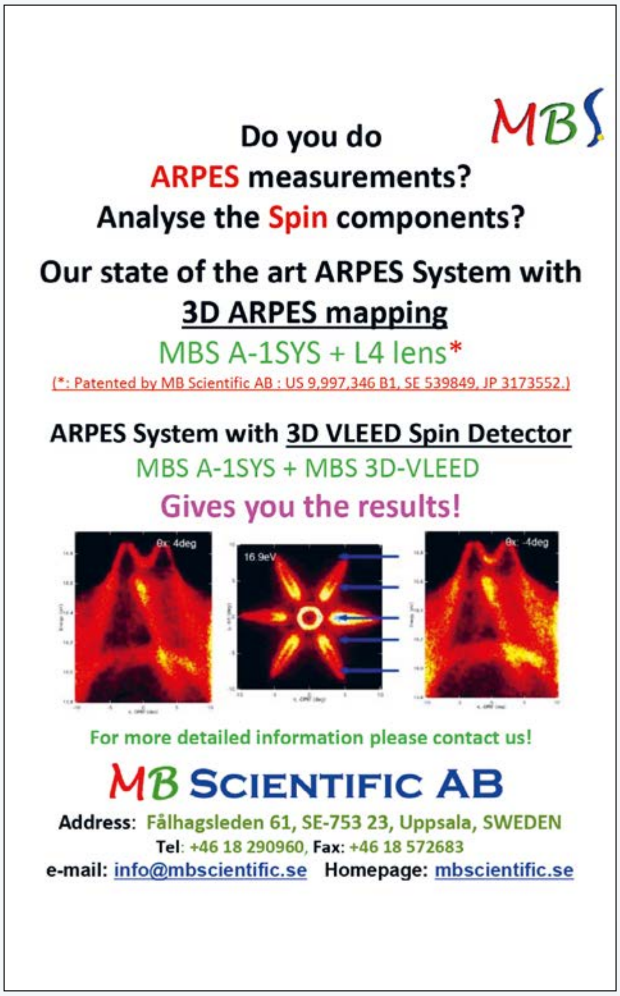
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[EPS EDITORIAL]

Welcome to our new Associate Members!

Following our survey among many companies and technical universities across Europe (see issue 52/3 of EPN), our policy of recruiting new associate members is starting to bear fruit, after three years of absence from any new membership.

Let us go back in time a little: In 2018, the European Physical Society (EPS) revised its associate membership programme. Three new categories were created: *The Prestige Sponsorship*, tailored for major partners' objectives, aims at funding the most prestigious prizes of the EPS. It even gives the possibility to create a new prize, with the name of the Associate Member, in partnership with an EPS Division or Group. *The Sponsorship for Societal Challenges* is committed with different EPS activities that facilitate the training of young researchers, help students working in developing countries, bridge the gap between school and university teachers, improve equal opportunities and outreach. Finally, *the Supporter Associate Membership* is designed for research institutions or medium-sized enterprises that seek global exposure through the EPS networks, conferences and events.

Although the benefits and rights associated with these memberships were numerous in terms of promotional offers, the success was not there. One probable reason is that the benefits only helped to improve public relationships. Things, however, seem to change today, as our Associate Members are now invited to participate in EPS events that will foster fruitful exchanges between researchers and industrial representatives, support early career researchers and network with other EPS members. Thus, Politecnico di Milano, the largest technical university in Italy with about 42,000 students, recently joined the EPS as its first Societal Sponsor. In addition, two Italian companies, CECOM, leader in high precision mechanics and ultra-high vacuum applications, and OCEM, leader in power electronics, became in turn Prestige Sponsor and Supporter Associate Member, respectively. Welcome to the EPS, which is your new home to partner with European physicists!

However, we do not forget our former associate members. IBM Zurich, ESRF/Grenoble and CAEN Group already accepted to integrate the programme committee of the future EPS Forum, the first day of which will introduce PhD students and postdocs to exciting research opportunities available in major industries and start-ups. Such an event will contribute to support the economic recovery in Europe.

Also the Joint Institute for Nuclear Research in Dubna, Russia, both associate member and historic site of EPS, signed a letter of intent at the beginning of the year to advertise and support the JINR Summer Schools in Physics. JINR will take in charge the local expenses of students attending its Physics Summer Schools, while the EPS will provide four grants per year for their travel costs. Details for attending are given in the section "EPS News" of the present EPN issue. Possible collaborations with the EPS Divisions and Groups of interest will be incented and JINR will create an EPS Young Minds section in Dubna.

Just for once, this editorial ends on a sad note. Taliban entered Kabul on August 15. The EPS fears for the safety and the freedom of Afghan physicists, and especially for women's access to science and education. We shall remain vigilant about the political situation in Afghanistan and its adverse consequences for our colleagues.

Finally, Claudine Hermann passed away on July 17. Claudine was the first woman appointed to a professor position at the prestigious Ecole Polytechnique in France. Honorary president of the Femmes & Sciences association which she co-founded in 2000 and president of the European Platform of Women Scientists since 2017, she tirelessly worked for gender equality in science. Her commitment to this cause was exceptional and she often collaborated with us to promote women in physics. Claudine was always available. She was a personality of rare quality and great kindness. She was 75 and we miss her today. ■

■ **Luc Bergé,** *EPS President*

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[FROM THE EDITORS]

Physics online

This year's summer conferences showed how well the physics community has adapted to the online world. After a year of online meetings and online teaching, physicists used their tools and experience to come together in conferences that were often postponed 2020 versions. In this EPN issue we put a few excellent examples in the spotlights. In their evaluations all organisers recognise and appreciate the much larger reach of the online events, but participants and organisers alike missed meeting in-person colleagues and friends. Our conclusion of this mini-survey: the International Physics Olympiad had the most impressive opening and closing ceremonies.

Also EPN is online, even at two locations. Shortly after submission to our publisher and long before arriving on your doormat, the issue is already stored in the open access repository at *epn.eps.org*. You can register for an alert and download the issue as pdf or read the flipbook version. Very handy for authors that are eager to share their contribution online in the social media. The feature articles are provided a DOI and shared at the website *europhysicsnews.org* which is kindly maintained by our publisher. However, please bear in mind that EPN is not designed as an online journal, it is optimised for print. We like it best on paper with a cup of coffee within reach.

In this issue the focus is on the field of nuclear physics. We thank our colleague Zsolt Fülöp for article suggestions and the first proofreading. In three dedicated feature articles, you are updated on the status and future plans of the field. The mini-theme is introduced by Marek Lewitowicz; Aurora Tumino, Jordi José and Marco La Cognata introduce you in facilities where beams of rare isotopes are being prepared; Niels Madsen is excited about spectroscopy of anti-hydrogen that is coming within reach; and Nathal Severijns shows how using free neutrino and radioactive atomic nuclei could shed light on new physics. In addition, two more exciting feature articles on low temperature physics are presented to you, that we could not publish in the previous issue of EPN, because of a lack of space. Silke Paschen and Qimiao Si elaborate on the phases – or faces – of strong correlations, and Richard Haley shows how the millikelvin barrier in nanoelectronic is being broken.

In conclusion, an EPN issue with excellent physics together with a peek into the eminent online performance of the community. For this, we are grateful to all authors for their contributions.

We hope that you have enjoyed the online physics this summer and could take a rest from a year of online teaching. We are curious to see what will be left from your experiences when slowly returning to 'physics as usual'.

We wish you all a pleasant start after the summer holiday season. ■

Conferences online

As a tribute to the organisers, EPN puts the spotlights on three international physics conferences and the international physics Olympiad for high school students which took place this summer. What is the heritage of a summer with online conferences and how inclusive are they? A mini-inventory.

The three conferences are the EPS High Energy Physics conference (EPS-HEP), the IUPAP 7th International Conference on Women in Physics (ICWiP) and the IUPAP International Cosmic Ray Conference (ICRC). All organisers creatively managed the online events having to deal with challenges such as world-round time zones and zoom-fatigue. It was appreciated that they published a Code of Conduct on their websites and made ample room in their schedules to reflect on the inclusiveness in their field, in particular on the status of women. The impressive repositories of material, including streams of talks and discussions form the heritage of the events. Together these are invaluable resources for education and outreach, but also for those physicists that cannot travel so easily. The low fees probably helped participants from less developed countries to participate more than ever. Now the challenge is to preserve the advantages and the level of inclusiveness, but get in-person contacts back again. ■

IUPAP ICWiP, 11-16 July 2021

https://wp.csiro.au/icwip2020/

Tools: Whoav app, Gather towns, Zoom, social media

One of the most amazing physics conferences is the International Conference on Women in Physics of IUPAP, the International Union of Pure and Applied Physics. About 80% of the participants are women physicists invited from around the world. The 7th edition of the conference was scheduled for 2020 in Australia, but postponed to an online version in 2021. The average conference fee was 100€. With more than 300 participants from more than 60 countries participation was higher than ever before. In particular this was true for the fraction of participants from less developed countries. Unfortunately, the rich repository of conference material is, at least presently, not freely accessible.

Almost any issue important for women in physics was included in the agenda. Conference workshops offered training in basic academic skills, but also provided ample time to review the status of women physicists in developing countries. New this year were advice on how to become a leader in science entrepreneurship, discussions on recognising intersectionality and about how male physicists could be allies for women in physics.

In addition, physics research was not forgotten. Early-career physicists presented their research posters while senior physicists presented their work at the plenary session. Among them was EPS' former President Petra Rudolf who presented her work in condensed matter physics and surface science. IUPAP's President Michel Spiro and President Designate Silvina Ponce Dawson highlighted plans for improving gender diversity in IUPAP. Among these, the proposal to adapt the statutes to ensure always having one woman and one man among the three leading positions of IUPAP: President, President Designate and immediate Past President. Similar rules are promoted for the leadership of the IUPAP workgroups and committees, award juries *etc.*

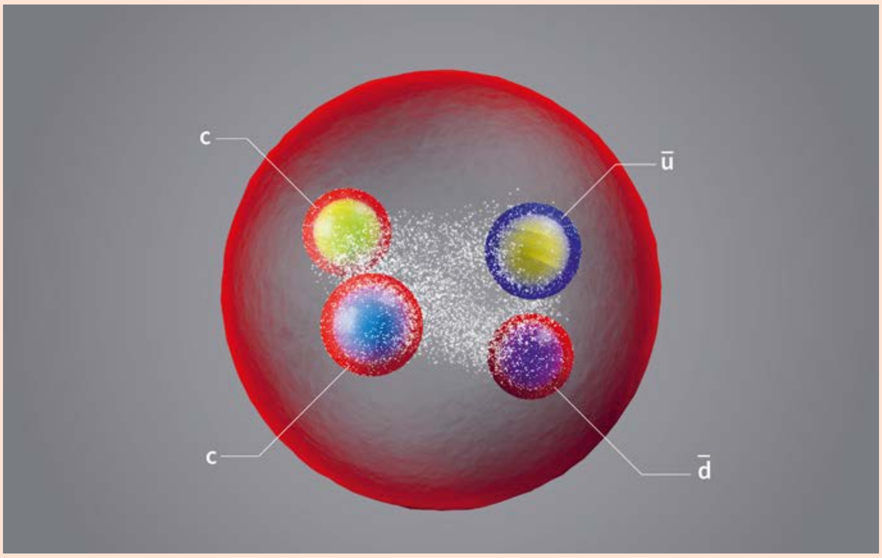
As follow up of the discussions, the conference formulated recommendations for IUPAP. Examples are the recommendation to encourage IUPAP members to organise workshops to provide skills on entrepreneurship and to call on them to provide opportunities for women in physics to have leadership roles. It was recognised that the high number of participants, and in particular the high fraction of women from Africa outside South-Africa and Asia outside South Korea, should be taken into account by IUPAP when considering future editions of ICWiP. ■

▼Group photo of ICWiP at the beach.

EPS-HEP, 26-30 July 2021

https://www.eps-hep2021.eu/

Tools: Zoom, Indico, Mozilla Hubs, social media



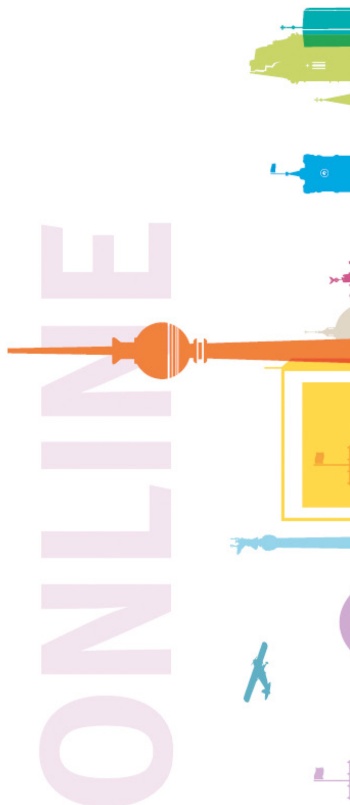
▲ Impression of T_{cc}^{+}, Daniel Domingues, CERN

The biennial European Physical Society Conference on High Energy Physics (EPS-HEP) is organised by the High Energy and Particle Physics Division of the EPS to review the field. The DESY institute in Hamburg together with the University of Hamburg were responsible for the online edition of 2021. More than 1800 participants, about twice the usual number, registered for the conference that was free of charge thanks to sponsor contributions by DESY, the University and the Cluster of Excellence Quantum Universe.

The local organising committee successfully mimicked the usual in-person conference. Routinely, *Zoom* and *Indico* were used for video communication and the online agenda. All talks and discussions were streamed. The poster session took place in virtual reality using the open-source platform *Mozilla Hubs*. For follow-up discussions the open-source chat platform *Mattermost* was used. All material is freely accessible via the time table at the *Indico* page https://indico.desy.de/event/28202/contributions. With 43 plenary talks, 13 review talks, 595 talks in 14 parallel sessions and 277 posters the repository is a valuable source for education and outreach and for those that could not attend the conference in real time.

One of the highlights of the conference was the first observation by the LHCb Collaboration of a new tetraquark, T_{cc}^{+} an exotic hadron with two charm-quarks, an anti-up and an anti-down quark. It is the longest-lived exotic hadron discovered to date and the first one with two heavy quarks and two light antiquarks. Theoretically there are two options: the quarks could be tightly bound or loosely bound in meson-meson molecule. The measurements are not yet conclusive on the best description of the new tetraquark.

With a code of conduct for the conference, multiple sessions dedicated to outreach, education and diversity and the evening talk – in German – by Christian Weinheimer about dark matter, the HEP community showed its commitment to inclusion and to society at large. At the conference the percentage of women convenors was more than 35%; the percentage of women in the scientific advisory committee and among plenary speakers was about 20% reflecting the current average percentage of women in the collaborations. ■



ICRC – 12-23 July 2021

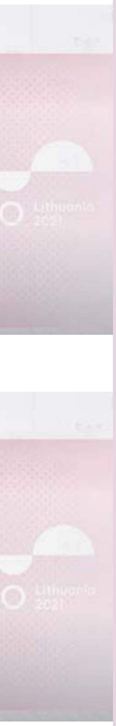
https://icrc2021.desy.de/

Tools: Zoom, Indico, Remo, social media

The IUPAP International Cosmic Ray Conference is one of the major conferences that every two years reviews the broad field of astroparticle physics. The 37th edition was organised 12-23 July by the DESY institute in Zeuthen, Germany. More than 1800 participants registered for the conference – more than twice the number of the previous edition in 2019. Participants came from 55 countries which is an increase of 40%; the total number of contributions went up with 23% to more than 1300. The average fee for participation was about 130€, much less than for earlier editions of the conference. As usual, for contributions in the parallel sessions the conference required to submit proceedings papers prior to the conference. Many are already freely accessible at https://pos.sissa.it/395. The plenary contributions will follow later. The public evening lecture by Werner Hofmann – in German – about astroparticle physics is stored at YouTube.

New for the online version was that pre-recorded 12 minutes presentations and for posters a 2 minutes flash talk had to be submitted together with a digital version of the slides/ poster. Also new were the 57 topical Discussion sessions, prepared by 2-3 convenors each, based on selected posters. These sessions were appreciated and well attended as could be seen from the online ratings – a feature that was introduced for all presentations. All streamed material will be made accessible for non-participants by the end of 2021 at least until the next ICRC in 2023.

At the Industry fair, companies set up their digital booth. For small occasional chats, more than 150 breakout rooms were created to have a coffee with friends or colleagues. For career development master classes on writing a scientific paper, a speed-date with recently-tenured physicists and a Job Board were offered. Inspired by the workshop on Sustainable High Energy Physics (https://indico.cern.ch/event/1004432), the sustainability of astroparticle physics was discussed with talks about sustainable conferences and travel, green computing and green experiments. An "eye-opener" according to participants. A first seed has been planted for possible change of the ICRC. ■



IPhO – 17-24 July 2021

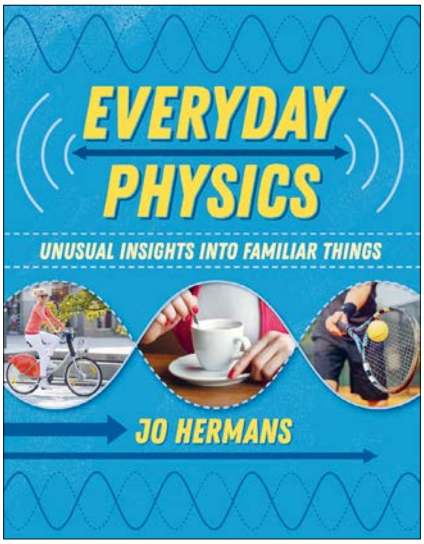
https://www.ipho2021.lt/

Tools: Zoom, daily newsletters, social media, in particular YouTube

Also the 51st International Physics Olympiad, the World Championship Physics Competition for High School students, went online hosted by Lithuania, after being postponed in 2020. National teams in 76 countries took the theoretical and experimental exams that were part of the contest. At home or at a central place in their country, the students competed in lab experiments with measuring the properties of capacitors and LEDs. The kits for the experiments were distributed to the teams in advance. Fair play was ensured by camera's and surveillance software. The theoretical exam was about planetary physics. The students had to calculate the effect of mid-ocean ridges on their surroundings and how seismic waves travel at the surface of a planet. The students got to know each other and at the same time the culture of Lithuania by daily newsletters and a rich programme of online social and cultural events. They participated in a Lithuanian dancing workshop, made together the traditional pink Lithuanian soup, played a Mindfight game and watched together a Lithuanian movie during the movie night. The opening and closing ceremonies were pre-recorded and were often watched together with family members. The closing ceremony included the announcement of the winners of the Olympiad. Traditionally, many students received honorary mentions and were awarded medals. Antonia-Alma Ghita from Rumania won the prize for the best female participant. Zhang Zhihan from China was the best theorist. The best experimentalist and absolute winner was Kim Kyungmin from South Korea. The amazing closing ceremony was done in the style of the international Song Contest with two professional presenters. You can watch it at YouTube (search for IPhO 2021 closing ceremony). In conclusion: the Lithuanian organisation, helped by many physicists in the participating countries, managed to make the online event a lively event. ■

Physics for everybody

Books on physics related to phenomena that we observe every day, such as 'The flying circus of physics' by Jearl Walker used to be quite common and popular. Recently, we witness that the internet has become the main educator - for better or more commonly for worse.



A gold mine of physics in the world around us, ranging from light to sound and from indoors to outdoors, written in a friendly style with beautiful diagrams, photos and explantions. Each chapter is a joy to read.
- Prof. Sanjoy Mahajan, MIT.

I've never seen a physics book look as 'friendly'. My pupils love it.
- Physics teacher

The book, 'Everyday physics' arrives at the right moment to bring together all those interested and give them resources to understand. A book, a long forgotten concept, is nevertheless a perfect vehicle here as all those issues will require revisiting and also searching from within. At the same time and most importantly, 'Everyday physics' comes from a reliable source with experience in communicating science, a former science editor of Europhysics News, Jo Hermans.

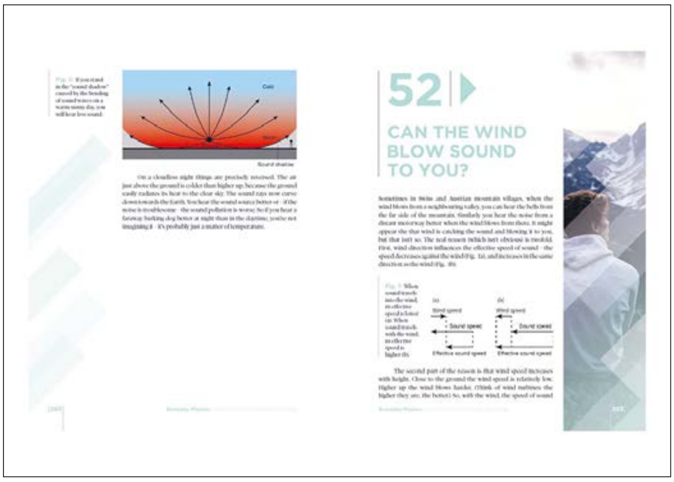
The author focuses on the topics that are part of general human experience. Starting with the Outdoors the book progresses through Vehicles, Vision, Sound and then it returns Home. It is true that it does not go for the cutting edge issues in physics such as results of the LIGO experiment, dark matter and energy but it certainly touches some very topical questions such as physics of GPS including a nod to Einstein and atomic clocks. Grouping of topics is, however, not so important as readers are encouraged to follow their own focus and find connections.

Goal of this book is to raise awareness of the world around us and to do so one has to entertain and educate. Using examples that we observe almost every day makes it possible to bring understanding of physics and science in general closer to the public. I am sure, however, that well educated and aware specialists cannot help being entertained and will find something to learn or appreciate in a new light. The tools that are used also include nice and precise yet simple graphs, photos as well as experiments that would be a delight in particular to the youngest. In this respect the book is for all levels of prior knowledge as it really is both entertaining and educational. On top of that it opens new doors.

As claimed by Eugene Ionesco 'It is not the answer that enlightens but the question', in this book readers are invited to propose new questions thus joining the circle of family and friends who provided the first batch. In that sense readers may reach an active relationship with science and that is to extend their knowledge enough to use it as a tool to engage their curiosity.

If you, like me, have never considered why waves arrive at the beach almost parallel to it then you are provided with both the issue and its resolution and you will never look at the beaches in the same way, pretty much like another book changed how I view walking on the wet sand. ■

Zoran Lj. Petrović
Serbian Academy of Sciences and Arts, Belgrade Serbia
Ulster University, Jordanstown, Northern Ireland, United Kingdom



In memoriam
Claudine Hermann (1945 - 2021)

On the 17th of July 2021, Claudine Hermann passed away at the age of 75.

Best-known for her tireless action in favour of gender equality in science, Claudine Hermann was an exceptional person by her wit and wisdom, her keen analysis of both scientific and societal problems, her dedication and commitment to helping others and the community, and her immense energy and tireless work ethics. Claudine was a physicist of the highest level, and a wonderful colleague respected by all.

Claudine obtained her physics degree in 1969. She defended her thesis in condensed matter physics, and more specifically, on the measurements of the Landé factor of the conduction electrons in GaSb, in 1976. This, and later research would prompt Claudine to formulate a highly cited critique of the manner in which k•p type band structure calculations were hitherto performed, and to propose significant improvements. Claudine occupied an assistant position at the École Normale Supérieure in Paris. She became the first woman professor at the École polytechnique in Palaiseau, France, where she was also the vice-president of the physics department from 1985 to 1992. Author of a monograph on statistical physics, Claudine's lectures were highly praised by all and loved by students, and her contributions to all aspects of training, education, and physics research at École polytechnique were numerous. We particularly cite her work on magneto-optics of metallic multilayers, on photoemission in activated semiconductors, and on optically detected magnetic resonance.

In the early 1990's Claudine started her action for the promotion of women in science. She joins the Demain la parité group in 1994, and co-authors several reports on young women's enrolment and position in engineering curricula and in university. With Noria Boukhobzan, Huguette Delavault, and Corinne Konrad, she published *Les Enseignantes-Chercheuses à l'université: demain la parité*. In 2000, Claudine co-authored the *Science policies in the European Union: Promoting Excellence through Mainstreaming Gender Equality* of the European Technology Evaluation Network of the Directorate General for Research of the European Commission. From 1999 to 2006, she would be an eminent member of the "Women and Science" group of the network. Claudine would go on to author more than forty articles, books, and other authoritative works, and has delivered countless lectures and addresses on the topic across the world.

Claudine Hermann was the co-founder and first president of the French association "Femmes et Sciences", president of the European Platform of Woman Scientists, and a very active member, till the last, of the "Femmes et Physique" Commission of the French Physical Society SFP. As such, Claudine also very actively participated in EPS activities. Notably, she regularly published in e-EPS, authored various editorials and columns, and was key in bringing about the EPS "Inspiring Physicists" calendar.

With the passing of Claudine, our community loses one of its most exceptional members. Her efforts to the advancement of the cause of women in science are no less than remarkable, and the example she sets unparalleled. Citing Claudine as she expressed herself in 2013: "Many young women ask me whether I am a feminist. If being a feminist means working for women to participate fairly and equally in society, then, 'yes', a resounding 'yes'!" ■

JINR-EPS Cooperation

Joint Summer Schools in Physics

The Joint Institute for Nuclear Research (JINR) is an international, world famous intergovernmental organisation located in Dubna, Russia. Historic Site of the EPS, JINR is a unique example of integration of fundamental theoretical and experimental research in nuclear, particle and accelerator physics with developments and applications to cutting edge technology and university education.

On 20 January 2021, a delegation of the EPS met online with the Directorate of the Joint Institute for Nuclear Research (JINR). This meeting launched prospects for joint initiatives, in particular the opportunity for the EPS to support Physics Summer Schools for young scientists and establish closer contacts between relevant EPS scientific divisions and groups and the JINR Scientific Council. A second meeting was held on 18 June to go through areas of common interest for further cooperation. Theoretical physics, particle physics, nuclear physics, and high-performance computing were identified as promising realms for co-organising schools, conferences and participations to future programme advisory committees. The EPS will invite its Divisions and Groups of interest to delegate one or several of their Board Members to join JINR scientific committees. From its side, JINR will organise an EPS Young Minds Section in Dubna.

These discussions resulted in the signature of a letter of intent between EPS and JINR. JINR will take in charge the lodging and local expenses of students attending its Summer Schools. The EPS will provide 4 grants of €500 per year covering the travel costs. An open call for applications will be managed by JINR. Applicants will only need to send their CV and a letter of reference. A panel involving representatives from EPS and JINR will evaluate the applications and make recommendation to JINR Director and EPS President who will endorse the choice of the selected students.

The EPS supports the JINR Summer School programme and invites its community of young researchers to register on http://students.jinr.ru/en for the coming Summer Schools expected to restart on-site from autumn 2021. They are also invited to enjoy the free-of-charge INTernational REmote Student Training (INTEREST) online courses (http://INTEREST.jinr.ru/).

If you are interested in these events, contact Ms. Ophelia FORNARI (ophelia.fornari@eps.org), Personal Assistant of the EPS Secretary General, or Prof. Stanislav Pakuliak, JINR UC Director (pakuliak@jinr.ru). ■

Authors: Luc Bergé – EPS president, Eliezer Rabinovici, Gertrud Zwicknagl – Members of the EPS Executive Committee – and Radu Constantinescu – Chair of EPS European Integration Committee. All authors are members of the Working Group 3 on cooperation with Eastern States.

▼ JINR-EPS cooperation

Physics for society: Grand challenges in the horizon 2050

Organised by The German Physical Society (DPG) [on the occasion of the DPG 175 years Anniversary] and the European Physical Society (EPS)

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The Young Minds Leadership Meeting 2021
a virtual experience

Richard Zeltner, Hripsime Mkrtchyan & Carmen Martín Valderrama
EPS YM Action Committee – DOI: https://doi.org/10.1051/epn/2021401

The Young Minds (YM) programme of the European Physical Society (EPS) was initiated 10 years ago, with the goal to connect young students and researchers all over Europe and to support their professional and personal growth.

The programme now comprises more than 60 sections being active in over 30 countries. A highlight of the annual agenda of YM is the leadership meeting, which is hosted by a section and brings delegates from all over the YM network together. The still high-case numbers and the dynamic situation in Europe regarding the Corona-pandemic made a physical meeting in 2021 impossible, such that the meeting was transferred into the virtual realm. Given the large number of delegates attending, as well as the many lively and open discussions that took place, the meeting on May 7 can be considered a large success.

A big advantage of the virtual format was that no budget or logistical restrictions limited the number or availability of participants. Consequently, the meeting was open to anyone in the YM network and eventually attracted 55 section delegates, representing more than 30 sections and 21 countries from Europe and the Mediterranean. The delegates came from various career levels, ranging from bachelor students to postdocs.

Traditionally, the meeting comprises two parts: a part focused on professional development, and a part devoted to stimulating exchange and networking among the attendees. Hence the virtual meeting was divided into two parts as well, the first taking place on Zoom and the second part on the more interactive platform Gather Town. On Zoom EPS YM programme manager Ophélia Fornari welcomed the participants, gave a brief overview of the history of EPS YM, and described the new functionalities for section management on the EPS website to the participants. Her presentation was followed by Richard Zeltner, EPS YM Action Committee Chair, who gave a wrap-up on the years 2020 and 2021 from the YM perspective and highlighted the numerous section activities that were carried out despite the ongoing pandemic. Since the meeting was the first of its kind for several new sections that were created during the pandemic, he also gave a quick overview of the grant application process and the ways YM sections can share their work with the broader physics community in Europe, *e.g.* via publishing in e-EPS or EPN. He also gave an outlook on the plans for the rest of the year and 2022 and thanked the members of the Action Committee that left the programme over the course of the last two years, in particular Petra Rudolf who handed over the EPS presidency, and thus the position in the YM Action Committee, just in April. As the third speaker, Luc Bergé, current EPS president, presented the agenda for his presidency and his plan to establish the EPS Forum to the YM community. Since a majority of young physicists eventually pursue a career in the private industry sector, his explanations on his plans to strengthen the relationships between EPS and the industry were followed with great interest by the audience. Eventually the first part of the meeting was concluded by a panel discussion on career advice for young scientists. Our distinguished guests Dr. Gabrielle Thomas, Dr. Lucia Santamaria, Dr. Luc Bergé, Dr. Chang Kee Jung and Dr. Petra Rudolf brought a very diverse set of experiences and backgrounds to the table. The open discussion on topics ranging from the role of professional media platforms for personal branding over the difference of working in academia and industry to the importance of aligning career choices with individual aptitudes and talents stimulated a large number of questions from the YM audience and was certainly a highlight of the event.

After the panel discussion the meeting transitioned to Gather Town, where the participants could engage in more informal and direct activities. During a speed networking event the delegates had the opportunity to refresh old connections and to create new ones within the YM community. Considering that the last direct exchange between the Action Committee and the sections took place during the leadership meeting 2019 it was also a great opportunity for the committee to get to know the new section officers in the established sections and to establish a relationship with the newly created sections. This was followed by a Physics Quiz, kindly provided by the hBar Omega Section Erlangen, in which the delegates mixed-up again, teamed in small groups and tested their knowledge, not only on physics but also on questions of popular science. After the physics quiz the official part of the meeting was concluded, but the Gather room remained open and many delegates stayed a bit longer and deepened their newly created connections.

Considering the large number of delegates, the many represented sections, the very active participation of the attendees over the full programme and the very positive feedback that the Action Committee received during and after the meeting, the virtual leadership meeting 2021 has been a large success. Hosting the meeting online allowed more delegates than usual to attend the meeting and reduced the logistical barrier for participation for delegates that might, for example, require a visa to travel. Hence the meeting provided a great opportunity to strengthen the connections to sections which are otherwise not frequently attending physical leadership meetings. Finally, for the sections that started their activity in 2020 and 2021 the meeting was a great chance to gain more insights into the programme structure and to connect with the network. However, even though the meeting has been a large success we are very much looking forward to connecting with the YM community physically again soon. The Action Committee just started with the preparation of the Leadership meeting 2022, which is planned to be co-located with the first EPS Forum. Thus 2022 will not only bring back physical meetings but will also bring Young Minds even closer to the broader European physics community. ■

by **Marek Lewitowicz**
Chair of Nuclear Physics European Collaboration Committee – DOI: https://doi.org/10.1051/epn/2021402

Modern Nuclear Physics in the European research Landscape

Physics of atomic nuclei and their constituents undergo transformations and develops towards more and more interdisciplinary field of research. Three articles published in the present issue of Europhysics News on nuclear astrophysics, spectroscopy of antihydrogen and search for new physics at low energies perfectly illustrate the new facet of nuclear physics research.

All major European infrastructures in this domain which are currently under construction, upgrade or commissioning as FAIR in Germany, GANIL-SPIRAL2 in France, ISOLDE at CERN, SPES in Italy, ELI-NP in Romania and future ISOL@MYRRHA in Belgium include in their scientific program and design new exciting opportunities in nuclear physics and at the same time in search for physics beyond the standard model of particle physics, astrophysics, atomic physics, nuclear medicine, solid state physics and numerous applications for society.

The recent detection of gravitational waves from a neutron star merger by the LIGO-VIRGO collaboration, followed by the observation of electromagnetic radiation by numerous telescopes, boosted experimental and theoretical physics in many domains, not least nuclear physics, particle physics and astrophysics. In particular, the equation of state of nuclear matter and scenarios of nucleosynthesis have been, and will be further, confronted with such observations. For nuclear physics, and indeed all physics communities, this extraordinary discovery is imposing a new interdisciplinary approach to research. In this context, several new initiatives reinforcing collaboration between astroparticle, nuclear and particle physics were initiated by ECFA (European Committee for Future Accelerators), NuPECC (Nuclear Physics European Collaboration Committee) and APPEC (AstroParticle Physics European Consortium) are playing the major role in the development of particle, nuclear and astroparticle physics at the European and international level. Organisation of joint seminars, interdisciplinary expressions of interest and joint diversity charter are among the most important actions actively supported by the three committees (see http://nupecc.org/jenaa/).

Since 1991, NuPECC, together with the whole community, regularly prepares and publishes a Long-Range Plan (LRP) in nuclear physics. Past editions of the LRP as well as the most recent one published in 2017 have been essential to identify opportunities and priorities for the nuclear science in Europe and provide the ministries, national funding agencies and European Commission with a framework for coordinated advances in the discipline. The next LRP which will be elaborated in a coming few years should fully explore interlinks and mutual fertilisation between nuclear physics and neighbouring fields of research. ■

NuPECC
Nuclear Physics European Collaboration Committee

RARE ISOTOPE BEAMS IN ASTROPHYSICS

A. Tumino[1,2], J. Jose[3], M. La Cognata[2] – DOI: https://doi.org/10.1051/epn/2021403

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Unstable isotopes govern the late evolution of stars and their explosive phenomena, such as novae, supernovae, x-ray bursters and neutron star mergers. Most of them are still out of reach of terrestrial experiments. Upcoming facilities will allow scientists to produce/observe them and shed light on fundamental questions about our universe.

Rare isotopes and their astrophysical origin

Only a small fraction of the existing nuclei is stable, about 250 in total. All the elements have isotopes that are unstable and disintegrate, or decay, by emitting radiation. Some nuclei have no stable isotopes and eventually decay to other elements. Unstable nuclei are numbered several thousands, and most of them have not been observed yet. Especially rare isotopes – unstable nuclei with extreme neutron-to-proton ratios - are still uncharted. Where do they come from? Once the Big Bang was ruled out as a major nucleosynthesis site, efforts focused on nucleosynthesis in stars (Hoyle 1946). Follow-up studies outlined the key role played by stars as nuclear crucibles where most of the cosmic elements have been (and are being) forged, but observational evidence of their contribution to the galactic abundances was yet missing. The detection of technetium in the spectra of some giant stars (Merrill 1952) provided smoking-gun confirmation to this hypothesis. Technetium is, in fact, the lightest species with no stable isotopes. Since its longest-lived isotope has a rather short half-life, $T_{1/2}(^{98}Tc) \sim 4.2$ Myr, compared with the age of the universe, its detection proved that nucleosynthesis is an ongoing process. Further evidence in this regard has been provided by the detection of other radioactive nuclei, such as ^{26}Al or ^{44}Ti.

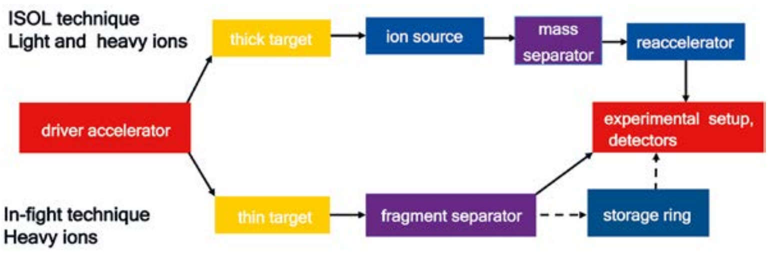
Since then, many unstable isotopes have been identified as major players in a suite of astrophysical scenarios. Classical novae, for instance, are powered by the decay of the short-lived, β^+-unstable nuclei ^{13}N, $^{14,15}O$, •••

▲FIG 1: Left: Tarantula Nebula in the Large Magellanic Cloud. Supernova 1987A is clearly visible as the very bright star in the middle right. Image taken with the ESO Schmidt Telescope. Right: Tattered remains of a supernova explosion known as Cassiopeia A (Cas A), the youngest known remnant from a supernova explosion in the Milky Way. Image taken with the NASA/ESA Hubble Space Telescope

and ^{17}F, that must be carried away by convection to the outer, cooler envelope layers to escape destruction by proton-capture reactions. Synthesis of ^{22}Na in novae has been predicted to be potentially observed through the 1275 keV gamma-ray line. In a somehow related scenario, type I X-ray bursts, the main nuclear path is delineated by the proton-drip line and by the presence of certain waiting-point nuclei, such as ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar. Light curves from type Ia supernovae are in turn powered by the decay chain ^{56}Ni→^{56}Co→^{56}Fe. The first unambiguous detection of the early 158 keV and 812 keV ^{56}Ni γ-ray lines and late 847 keV and 1238 keV ^{56}Co lines has been reported for SN 2014J, the closest type Ia supernova detected since the advent of γ-ray astronomy. The distribution of ^{26}Al in our Galaxy and its correlation with ^{60}Fe has provided valuable inputs to link their origin to massive progenitors (most likely, core-collapse supernovae), helping in turn to better constrain models of these explosions.

Synthesis of rare nuclei beyond A ≈ 60 takes place mostly entirely by exposing lighter seed nuclei to a source of neutrons. Such a mechanism provides a natural explanation for the fact that the solar system abundance curve peaks near the mass numbers A ≈ 84, 138 and 208, corresponding to the neutron magic numbers of N = 50, 82, and 126, respectively. The neutron capture may be either slow (s-process) or rapid (r-process), mostly depending on the flux of neutrons. In particular, the r-process, whose production site is yet to be self-consistently identified (core-collapse supernovae and/or neutron star mergers?), is activated under a so large neutron exposure that the decay constant of an unstable nucleus (such as ^{130}Cd, ^{131,133}In or ^{160}Gd) created after neutron capture is small compared to the decay constant of the competing (n,γ) reaction ($\lambda_\beta << \lambda_{n\gamma}$). In this case, the nucleosynthesis path runs close to the neutron dripline.

▼FIG 2: Simplified scheme of production of radioactive nuclear beams with ISOL technique and in-flight separation.



Facilities and techniques

Dedicated facilities have been built to produce and accelerate radioactive nuclides to study their nuclear properties and interactions. Two methods are mostly used to carry out such studies: the isotopic separation online (ISOL) and the in-flight separation (Gelletly 2000, Blumenfeld 2013).

In the ISOL technique, the radioactive nuclei are created from the interaction of a stable (or neutron) beam hitting a thick target. A medley of nuclides is generated inside the target and the species of interest is separated from the others after being extracted, for instance by diffusion, and injected into an ion source. Then, it is reaccelerated onto a secondary target to induce, for instance, the nuclear reactions of astrophysical importance.

The main advantage of ISOL facilities is the availability of high-quality beams, in terms of intensity and focusing, the latter being comparable with those of stable-ion beams. However, the range of available isotopes is rather limited since some of them have too short lifetimes for enough nuclei to survive the delay times of the ISOL method (from ~10 milliseconds for ion guides and gas catchers or high-temperature target assemblies to hours or more, *e.g.*, in the case of batch-mode production).

ISOL facilities include the pioneering laboratories at Louvain-la-Neuve (Belgium) and ISOLDE (CERN, Switzerland), second-generation facilities such as SPIRAL2 (GANIL, France) and FRIB (NSCL, USA), and forthcoming ones such as SPES (LNL, Italy).

The in-flight separation technique opens to the investigation of radioactive ions with lifetimes of microseconds. High-energy beams (hundreds of MeV) of heavy nuclei are driven onto thin targets to induce fragmentations. The kinematic conditions lead to fast forward-focused cocktail beams; fragment separators are placed downstream to single out the radioactive beam of interest that is focused onto a secondary target to carry out nuclear reactions. However, beam quality in terms of energy spread and angular focusing is usually worse than in the case of ISOL beams, and beam energy fine tuning is more complicated to achieve. An additional advantage of in-flight production is the possibility to inject freshly produced radioactive ions into a storage ring, as planned at GSI, Germany, where CRYRING will make it possible to recycle and slow the ions down to about 100 keV/u, opening interesting opportunities for nuclear astrophysics.

In-flight facilities worldwide include FRIB (NSCL, USA), LISE (GANIL, France), RIBF (RIKEN, Japan), with several smaller scale facilities like TwinSol at the Notre Dame University (USA) or SOLEROO at the Australian National University.

As foreseen by the FRIB long-range plan, soon about 80% of the isotopes predicted to exist for elements up to uranium and beyond will be produced and investigated.

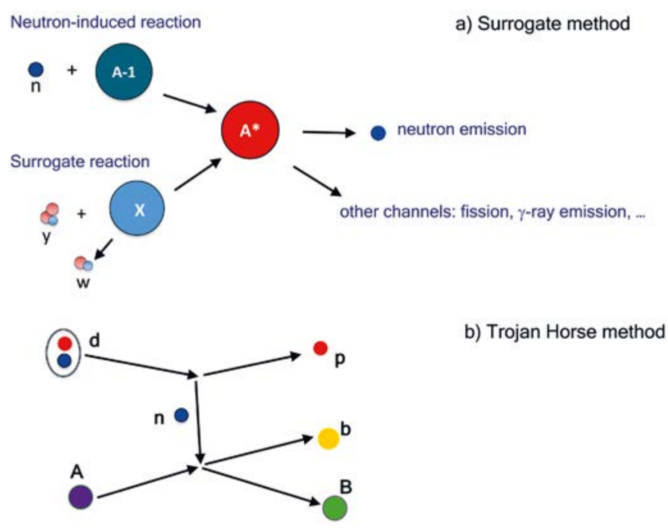
Nuclear inputs and methods

Impressive progress has been achieved to perform laboratory measurements with rare isotopes, despite intrinsic difficulties, such as extremely small cross sections, low beam intensities or the absence of appropriate radioactive targets. Charged-particle reactions on short-lived nuclei are usually measured in inverse kinematics using hydrogen and helium targets, with recoil separators to detect and identify the recoiling products and to reject the beam. The pioneering measurement with a rare-isotope beam was $^{13}N(p,\gamma)^{14}O$ using a ^{13}N beam (3×10^8 particles/s) produced at Louvain-la-Neuve. A successful experimental method to study the properties of resonances is the resonant elastic and inelastic scattering, which has provided an extensive amount of data on unbound states in proton-rich nuclear systems relevant to reaction rates in explosive burning scenarios. With rare isotope beams, a thick-target is often used, where the beam is stopped and β-γ spectroscopy is performed to study electromagnetic decay of isomeric and excited nuclear states, and to measure gamma rays following beta-decay of excited states into the daughter nuclei. The stopped beam spectroscopy may also offer information on exotic decay modes such as β-delayed proton(s) or neutron(s) emission in the nuclei toward the drip lines. Nuclear mass measurements are also needed in the modelling of various nucleosynthesis processes, in particular r-process pathways, with typical masses larger than 50 GeV/c^2. Two distinct classes of techniques exist: determination of Q-value through reactions or decay; direct mass measurement through mass spectrometry, time-of-flight, cyclic/frequency measurements.

To access the reaction rates, indirect techniques are also employed and in some cases are the only viable alternative. One such technique is the surrogate method (Escher *et al.* 2007), mainly used for neutron capture reactions: a surrogate X(y,w)A* reaction is used to populate the same A* compound nucleus of the (n,γ) reaction and then the desired decay channel is measured. The method relies on the assumption that the decay of the compound nucleus is independent of the entrance channel. Another indirect approach, the Trojan Horse method (Tumino 2021), exploits a quasi-free A(d,bB)p transfer reaction to determine the cross section of the A(n,b)B reaction at astrophysical energies: deuterons are used as virtual n-targets, with the remaining proton acting as a spectator in the A+n interaction.

Conclusions

Nuclear reactions involving rare isotopes determine the signatures of elemental and isotopic abundances found in the spectra of any astrophysical object. This is a major reason why the rare isotope science is the trending topic of nuclear research worldwide. Rare isotope beams in nuclear astrophysics represent the beginning of a new era of exploration and discovery that will challenge experimentalists and theorists alike. ■



▲ FIG 3: a) The surrogate-reaction method in a schematic representation. The surrogate reaction is here a transfer reaction X(y,w)A*. b) The Trojan Horse method for neutron induced reactions represented with its characteristic pole diagram. The upper vertex shows the deuteron break-up, while the lower vertex the A(n,b)B neutron induced process.

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Marco La Cognata is a researcher of the INFN, Italy, and coordinator of the INFN-LNS nuclear physics activities. His research activity focuses on nuclear astrophysics, mostly with indirect methods.

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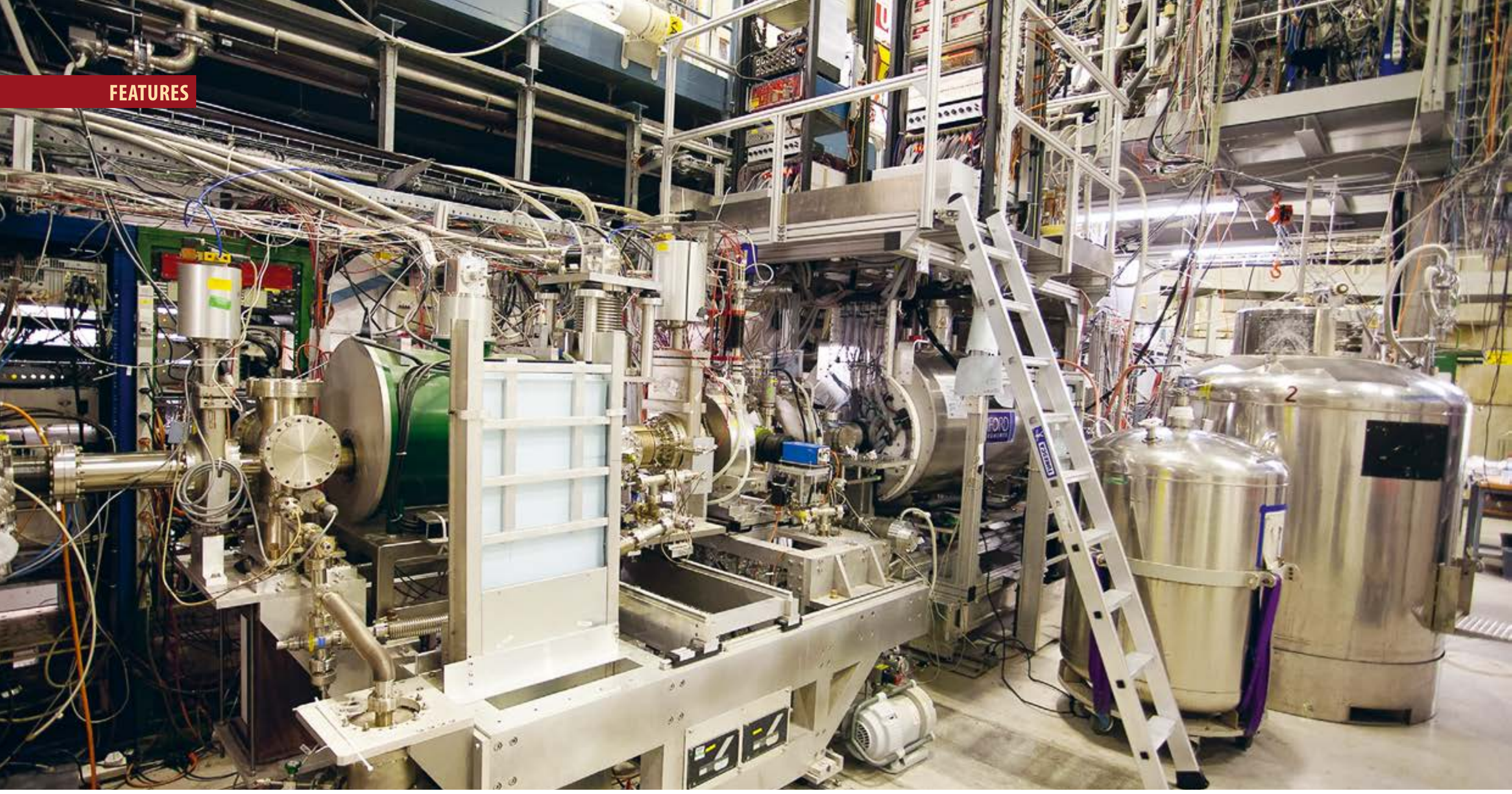


SPECTROSCOPY OF ANTIHYDROGEN

Niels Madsen – Swansea University, United Kingdom – DOI: https://doi.org/10.1051/epn/2021404

In 2017 the first observation of an optical transition in an anti-atom was announced by the ALPHA collaboration. This marked a new era in using precision measurements to help unravel one of the most profound questions of modern physics; why the Universe is predominantly made of matter.

▲ View of the ALPHA experimental setup. Antiprotons arrive from the AD from the left and enter first the Antiproton Catching Trap (green cylinder). Subsequently, they are merged with positrons in the Atom Trap (horizontal cylinder at the center of the image)

Antihydrogen, the bound state of a positron and an antiproton, was first made at CERN in 1995. It's a testament to the difficulty of this task that the constituents, the positron and the antiproton, were discovered in 1933 and 1955 respectively [1]. The intense interest in antihydrogen reflects the central role hydrogen has played in the development of quantum physics, from Fraunhofer lines in the solar spectrum, over the Balmer series, to the Lamb shift, hydrogen has, due to its simple structure, played a key role in developing a quantum mechanical understanding of the microscopic world. Hydrogen is thus the best understood atom in the periodic table and can be described theoretically from first principles. At the same time, antimatter, or more precisely, the virtual absence of antimatter in the Universe remains an unresolved asymmetry. The famous Sakharov conditions for an asymmetric universe remain a guide for searches, but so far the asymmetries discovered do not lead us to the Universe we observe.

Hydrogen has also helped drive another development, that of precision spectroscopy, and in particular precision laser spectroscopy, where the current record is a measurement of the ground to first excited state (1S-2S) transition to about 15 decimal places of precision [2]. This sort of measurement (though not in hydrogen) is the cornerstone of optical atomic clocks, devices that have recently reached a staggering 18 digits of precision [3]. The technology that has ensued, in particular, the frequency comb developed by Hänsch and Hall [4], has allowed absolute frequency measurements with a significantly more manageable setup than in the past.

To study antihydrogen it needs to be synthesized. Antiprotons are sourced by capturing antiprotons produced in high energy collisions and positrons typically from a radioactive source. These particles are then often manipulated and merged in Penning traps to form antihydrogen that can be trapped using a magnetic minimum trap. An example of the central part of the ALPHA experiment to synthesize, trap and study antihydrogen is shown in figure 1. With this state-of-the art apparatus the ALPHA experiment captures about 20 antihydrogen atoms every four minutes and have accumulated more than 1000 atoms in the magnetic trap thus opening the door to very precise scrutiny of the anti-atoms [1,5].

Combining advances in precision spectroscopy with advances in antihydrogen synthesis thus holds the promise for extremely accurate comparisons of matter and antimatter that may lead to the discovery of a difference between them that has so far eluded other approaches.

Spectroscopy

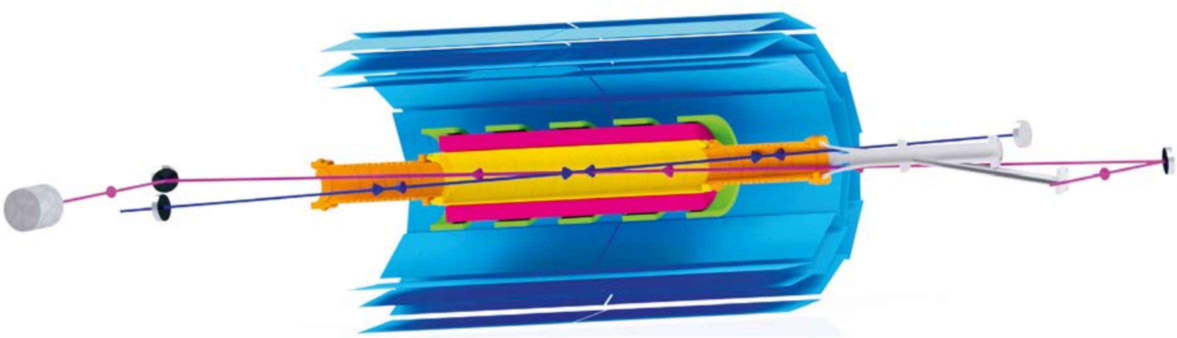
The headline transition sought in hydrogen and antihydrogen is the dipole forbidden 1S-2S transition already mentioned. As it is dipole forbidden, two photons need to be emitted for a decay and the lifetime is thus very long (about 1/8 of a second), and the linewidth correspondingly narrow. This narrow linewidth and the elimination of the first order Doppler shift by using two photons for excitation is key to the spectacular precision of the hydrogen measurement, and thereby its promise of the most precise comparison of hydrogen and antihydrogen.

However, when looking for symmetry violations, it must be kept in mind that different transitions depend differently on the underlying interactions. Furthermore, the (anti)proton charge radius influences the energy levels (see *e.g.* The Proton Radius Puzzle [6]). There is therefore ample motivation to study several other transitions amongst which the most prominent are perhaps the ground state hyperfine splitting and the 2S Lamb shift.

In contrast to hydrogen, which can be difficult to detect, antihydrogen annihilates on impact with matter, and the ~2 GeV of energy released from the antiproton annihilation, mostly in the form of pions, is easily detectable, such that, under the right circumstances, the loss of a single antihydrogen atom can be observed. This sensitivity allowed the first trapping to be confirmed and has also served as the workhorse for all subsequent measurements. The initial trapping in 2010 and subsequent improvements has allowed the ALPHA experiment to measure the hyperfine splitting, the 1S-2S transition, and the 1S-2P transition, with the latter recently allowing the first laser-cooling of antihydrogen [7]. The measurement of the 1S-2S two photon transition stands out by achieving a record (for antihydrogen) precision of 2×10^{-12}. The signal in these various measurements is based on intentional annihilation of antiprotons, achieved either by inducing a spin flip of the positrons or photoionization of the anti-atom. The precision of the 1S-2S measurement is limited by a combination of issues, prominently featuring the transit-time of antihydrogen atoms going through the laser beam. Both a larger laser beam and colder antihydrogen may improve this by narrowing the line width, the promise of the latter recently demonstrated by laser-cooling the antihydrogen atoms. Additionally, improvements in metrology (absolute frequency referencing) are being implemented by adding an active hydrogen maser and a Cs-fountain clock to expedite progress towards the same precision as in hydrogen.

Comparisons with Hydrogen

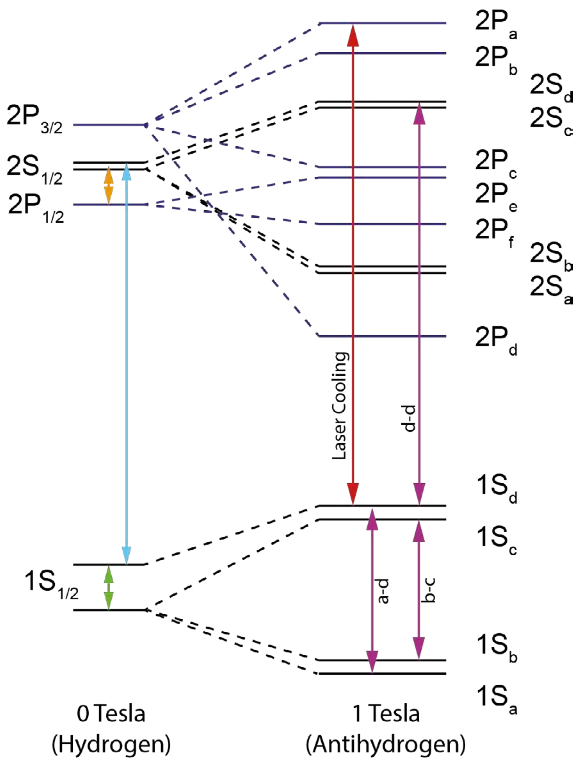
The beauty of antihydrogen as a probe for fundamental tests is that it is, at least in principle, possible to make completely model independent comparisons. However, one caveat of measurements on trapped antihydrogen is the presence of the magnetic fields used for trapping that induce significant shifts in the atomic transitions. Ultimately the 1S-2S measurement discussed in detail above, as well as other measurements, both planned and done, need to be compared directly to those in hydrogen. However, to truly do that in the most model • • •



▲ **FIG. 1:** Cut-out view of the central ALPHA antihydrogen apparatus. The green cylinders and the long purple cylinder mark the short solenoids and the octupole used for creating the 3D magnetic field strength minimum that serves to trap the antihydrogen atoms. The yellow cylinders are the central Penning trap electrodes that also surround the magnetic trap for antihydrogen synthesis. The sections with orange electrodes are used for preparation of positrons and antiprotons. An axial magnetic field of 1T to complete the Penning trap is supplied by a large solenoid surrounding the whole structure (not shown). Trapped antihydrogen can occupy a volume of around ½ liter. The blue laser-beam is the retroreflected 243 nm laser for 1S-2S two-photon excitation (it circulates in a cryogenic build-up cavity), whereas the purple (single pass) laser is the 121.6 nm laser for 1S-2P excitation and laser-cooling. The grey structures on the left allow microwaves to be injected for inducing hyperfine transitions. The blue panels are the main silicon wafers of the annihilation detector.

••• independent way, a measurement of hydrogen needs to be carried out in the same apparatus, using the same methods, preferably at (at least on average) the same time and also preferably at (near) zero electric and magnetic fields. We're still some way from that. ASACUSA recently made a first step in this direction by using the apparatus they have built for antihydrogen hyperfine measurements to make a hydrogen measurement [8]. The equivalent antihydrogen measurement is pending their ability to make a beam of ground state atoms, but the potential is for a field-free measurement as the antihydrogen is extracted from the synthesis region that necessarily has strong magnetic fields.

For 1S-2S spectroscopy, where significantly more (anti)-atoms are still needed, or at least longer interaction times, the trap still seems the best choice. Thus, antihydrogen compatible methods for loading traps with cold hydrogen must be developed, as must detection methods that do not use annihilations but are compatible with the current setup. The difficulty here is, as illustrated on figure 1 that we only have axial access to the central, cryogenic region, such that efficient photon detection is only possible with in-situ ultra-high vacuum, cryogenic compatible detectors integrated in the cylindrical structure of the Penning-trap electrode stack. However, once developed, such detectors will allow much more sophisticated measurements, also on higher lying states in antihydrogen necessary for the determination of the charge radius of the antiproton and the antimatter Rydberg constant.



▲ **FIG. 2:** Level diagram of (anti)hydrogen in no magnetic field and the 1 Tesla field used in the ALPHA trap. The hyperfine splitting of the 2P levels (in blue) are not shown. Precision measurements in hydrogen have been done near zero magnetic field and we have indicated the most famous splittings : the 1S-2S transition (light blue), the ground state hyperfine splitting (green) and the 2S Lamb shift (orange). For 1T (antihydrogen) we have indicated the main precision measurements, the hyperfine transitions in the 1S level and the 1S-2S transition (purple), as well as one of the 1S-2P transitions, namely the one used for laser-cooling (red).

Outlook

Spectroscopy of antihydrogen has come a long way from the early dreams more than 30 years ago, to the accomplishments of the last few years, heralding the most precise measurements of antihydrogen to date. While experimental and systematic challenges remain, the prospect of reaching the same precision as hydrogen now seems within reach for at least the 1S-2S transition, as does the prospect of determining the anti-atom Rydberg constant and the antiproton charge radius. Beyond that lies the exciting prospect of utilizing the full potential of the achievements making the comparisons with hydrogen truly model-independent by doing near-simultaneous measurements in the same apparatus. Antihydrogen spectroscopy is in for an exciting decade, if not more. ■

About the Author

Niels Madsen is professor in experimental physics at Swansea University and deputy spokesperson of ALPHA. He has worked on antihydrogen for 20 years, from the first low energy formation to trapping and spectroscopy.

“ In contrast to hydrogen, which can be difficult to detect, antihydrogen annihilates on impact with matter, and the ~2 GeV of energy released from the antiproton annihilation, mostly in the form of pions, is easily detectable, such that, under the right circumstance, the loss of a single antihydrogen atom can be observed. ”

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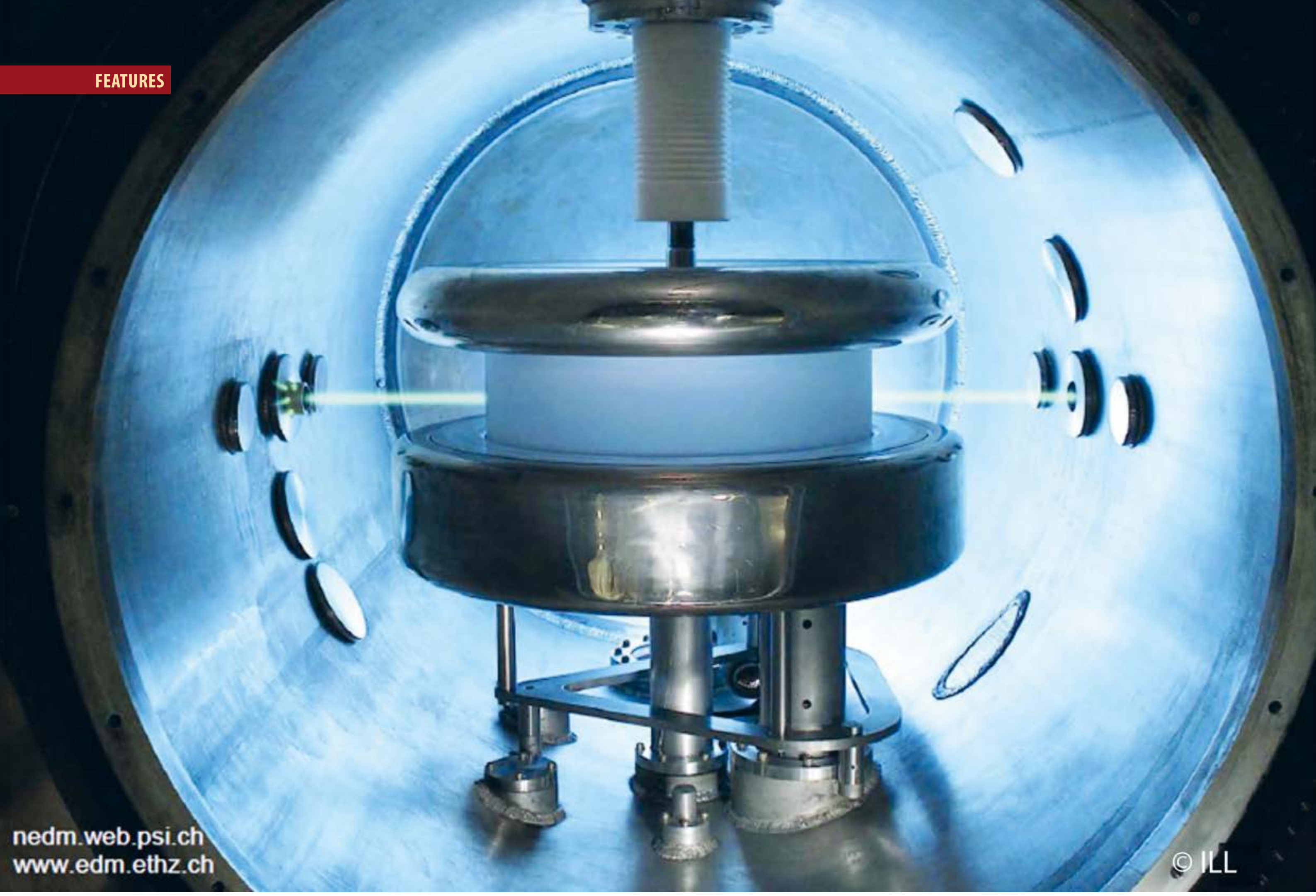

SEARCHES FOR NEW PHYSICS WITH FREE NEUTRONS AND RADIOACTIVE ATOMIC NUCLEI

N. Severijns – Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, Belgium – DOI: https://doi.org/10.1051/epn/2021405

The Standard Model of Particle Physics is very successful but does not explain several experimental observations. Extensions of it, invoking new particles or phenomena, could overcome this. Experiments in different energy domains allow testing these extensions and searching for new particles. Here focus is on low-energy experiments with neutrons and radioactive nuclei.

▲ nEDM inner view vacuum chamber. © ILL

The Standard Model of Particle Physics and beyond

The Standard Model of Particle Physics (SM) successfully describes the fundamental particles (quarks and leptons), and their interactions via the electromagnetic and the weak and strong nuclear forces by exchanging messenger particle 'gauge bosons' (the photon for electromagnetism). However, it does not explain a number of observed phenomena. Examples are the breaking of parity symmetry by the weak force (meaning that of a weak decay process and its three-dimensional mirror image only one effectively occurs in Nature), the precise nature of this force, and the difference between the amount of matter and antimatter in the Universe.

Extensions of the SM try explaining these phenomena by adding specific features or new gauge bosons. Experiments try to confirm or falsify these extensions, indicating the direction for future work. Best known are searches for new particles at high-energy colliders. A good example is the discovery of the Higgs-boson (related to the generation of the mass of all particles), at the Large Hadron Collider at CERN (Geneva). Here we focus on experiments at much lower energies, with free neutrons and radioactive atomic nuclei. Recent reviews of this field are found in *e.g.* [1-2].

The matter-antimatter mystery and electric dipole moments

A currently very active field of research is trying to shed light on the small difference between the amount of matter and antimatter that must have occurred in the very early universe. When all antimatter had disappeared in 'collisions' with matter particles, thereby generating the cosmic background radiation we observe today, a small excess of matter (about one particle in a billion) evolved to form the universe we observe today, and is the cause for us being here. Andrei Sakharov showed that such a difference can be explained by three conditions, one of these being a violation of the so-called CP symmetry. This is the combination of charge symmetry (C) and parity symmetry (P), which requires replacing in a physical process all particles by their antiparticles (C) and taking the (three-dimensional) mirror image of the process (P). If the resulting process is also observed in Nature, CP symmetry is said to hold, if not it is violated. Violation of CP-symmetry is observed in a certain class of particles (called K^0, B^0 and D^0 mesons), but this is too small to explain the observed matter-antimatter difference. Physicists therefore search for other, larger signals of CP violation.

A very popular observable violating CP symmetry is a permanent electric dipole moment (EDM), d, of a particle. First experiments started with the neutron in the 1950's (Fig. 1), and sensitivity has increased by about six orders of magnitude. The current best value was obtained in an experiment at the Paul Scherrer Institute (Switzerland). The result, $d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}$ e.cm [3], is consistent with zero. The high sensitivity is illustrated by the fact that if one would enlarge the neutron to the size of the Earth, the difference between the time-averaged position of positive and negative charges inside it should be less than several micrometers.

Permanent EDMs are also searched for in other particles, in atoms and in molecules [4]. Indeed, as many extensions of the SM include different CP-violating sources, these can only be distinguished when a variety of systems is studied. The highest-precision EDM results to date were obtained with ^{199}Hg and ThO molecules. Recently, interest has grown in octupole deformed nuclei as this was shown to enhance a possible EDM. As such isotopes are found in elements like Rn, Ra, Th, and Pa, with only radioactive isotopes, experiments require radioactive beam facilities, *e.g.* ISOLDE at CERN, Geneva or TRIUMF at Vancouver.

> **Experiments in beta decay have led Pauli to suggest the existence of the neutrino and uncovered several fundamental properties of the weak force, such as the violation of parity symmetry and the overall structure of the weak interaction.**

Studying the weak nuclear force in neutron and nuclear beta decay

The most elementary beta-decay process is that of the neutron, changing it into a proton via the creation of a W gauge boson (a weak force messenger particle), and causing emission of an electron •••

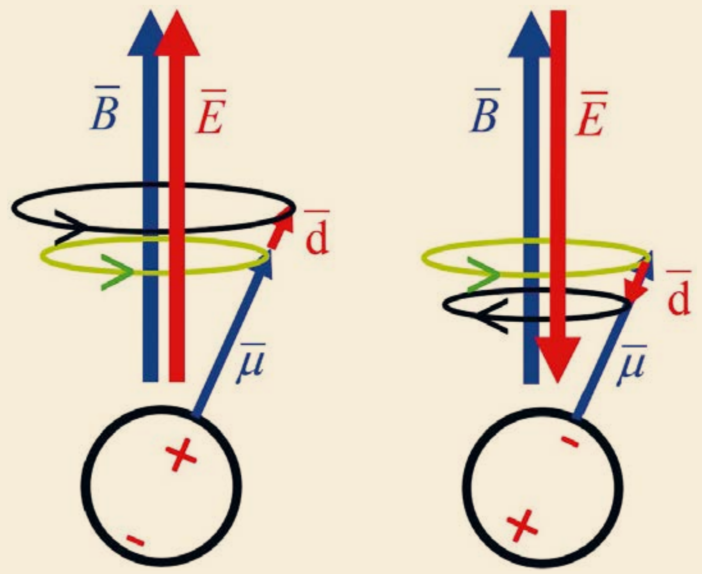

Fig. 1: a non-zero permanent EDM, ***d***, for the neutron would mean that the time-averaged position of positive and negative charges inside the (neutral) neutron would not coincide. This would cause a precession of the neutron spin when placed in an electric field, **E**. As the neutron has a magnetic moment, **μ**, which does not violate CP symmetry and causes a spin precession in a magnetic field, **B**, a non-zero EDM would cause a tiny difference in the neutron precession frequency when placed in alternatingly parallel (left) and anti-parallel (right) magnetic and electric fields.

••• and an electron-antineutrino (β^- decay). This occurs for a free neutron and for neutrons in radioactive nuclei with an excess of neutrons over protons. In radioactive nuclei with a proton excess, the inverse process (β^+ decay) can occur, changing a proton into a neutron with emission of a positron and electron-neutrino. Experiments in beta decay have led Pauli to suggest the existence of the neutrino and uncovered several fundamental properties of the weak force, such as the violation of parity symmetry and the overall structure of the weak interaction, *i.e.* the type of messenger particles that relate to it.

As the neutron (lifetime ~ 15 minutes) is a very simple system consisting of three quarks, it is an ideal probe for studying the weak force with few disturbing effects. In the beta decay of radioactive nuclei (with half-lives from a fraction of a second to billions of years), effects of the nuclear medium (*e.g.* virtual pion exchange) have to be included. However, the several thousand radioactive nuclei have very different properties, so that one can select the ones best suited for a given experiment. Important classes are those with an equal number of protons and neutrons, or a difference of just one (mirror nuclei).

One type of experiments determines the *ft*-value of a beta transition, which depends on its intensity and decay energy, and the half-life of the decaying state, corrected for percent-level effects. For so-called pure Fermi transitions this has provided a precise value for the *up-down* quark-mixing matrix element [4]. Similar measurements in neutron decay and for mirror nuclei are not yet competitive but are catching up [2]. The *up-down* matrix element is important for testing unitarity of the quark-mixing matrix, allowing to search for beyond-SM physics such as a fourth generation of quarks or new gauge bosons.

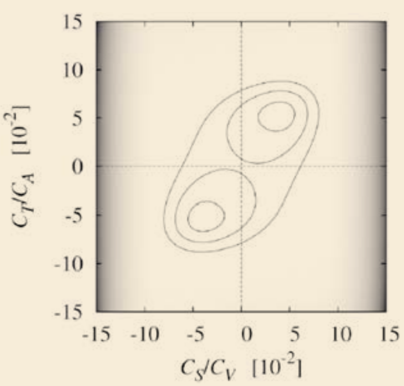

Fig. 2: result of the fit of nuclear and neutron decay data sensitive to scalar and tensor type weak interaction couplings (C_S and C_T) involving right-handed neutrinos, relative to the SM vector and axial-vector coupling constants C_V and C_A. The contours of constant $\chi2$ correspond to iso-$\chi2$ levels with values $\Delta\chi2$ = 1, 4, and 9. Based on these limits, scalar and tensor type weak interactions with right-handed neutrinos could in principle occur in up to about 10% of the beta decays. From Ref. [1].

So-called correlation measurements observe the relative emission angle between the spins and momentum vectors of the initial neutron/radioactive nucleus and its decay particles, *i.e.* the electron or positron and the recoiling nucleus (the (anti-)neutrino from beta decay cannot be detected). Almost always the energies of the decay particles are also measured. One can further choose to polarize the spin of the neutron/nucleus in the direction of an applied magnetic field. The forward-backward asymmetry in the electron emission with respect to the polarized neutron spin provides the relative strength of the two types of weak force observed in Nature, the ratio g_A/g_V [1]. Further, precise tests of the parity or time reversal symmetries [5] can be performed, the latter testing whether a physical process and the 'in time backward running' process occur with the same probability. One can, finally, also search for possible new components of the weak force driven by as yet unobserved messenger bosons. The latter would induce a small change in the values of experimental observables with respect to their SM value (*e.g.* Fig. 2). Information obtained is complementary to that from colliders [1, 2].

Of course, instrumental (systematic) effects always have to be carefully considered. In this respect, the possibility to perform extensive simulations of the behaviour of the experimental apparatuses, is a big asset. Together with advances in detection technology and analysis tools, this has allowed reaching precisions at the per mil level. As this requires taking in account also small contributions to the value of observables induced by the strong force (*e.g.* [1]), new challenges and new research possibilities now open up for this field. ■

About the Author

Nathal Severijns is full professor of physics at KU Leuven University with a track record in low-energy weak interaction experiments with spin-polarized and unpolarized neutrons and exotic nuclei. He has written several review articles covering this research field.

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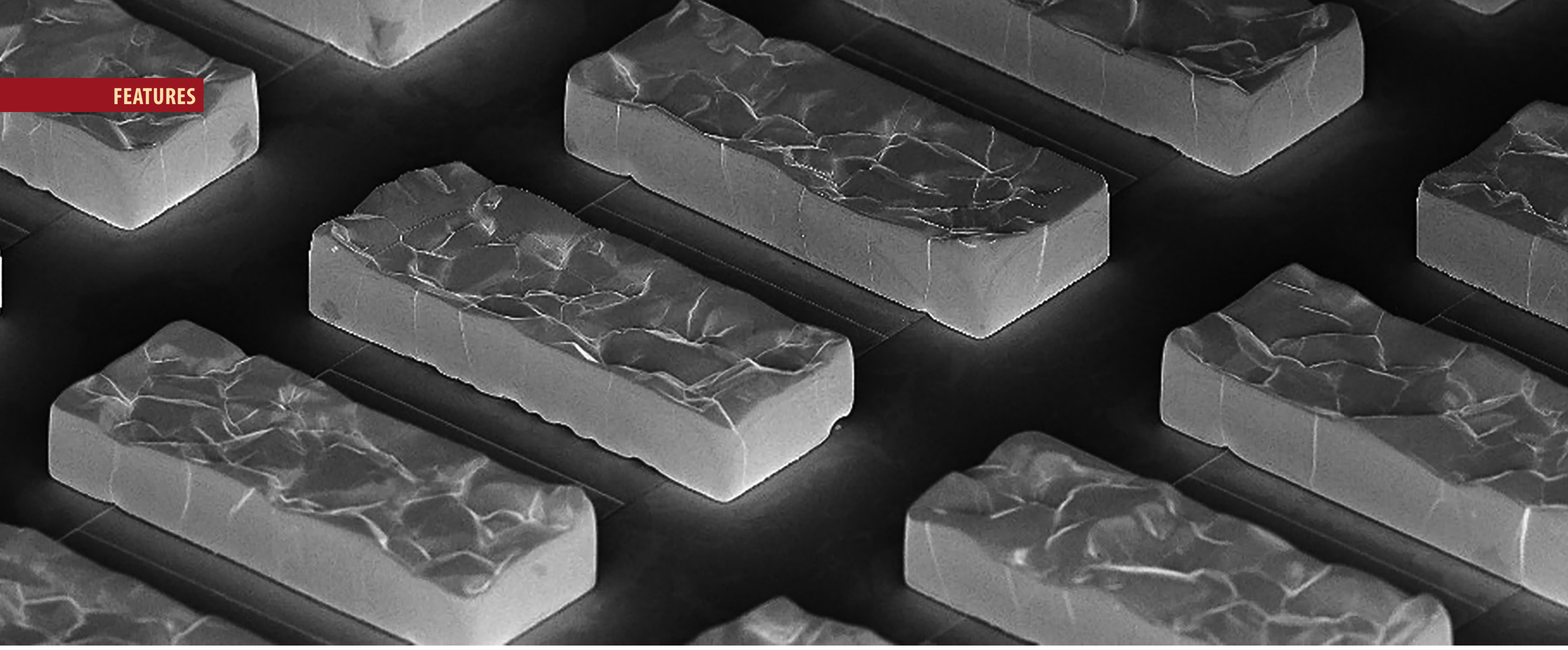


BREAKING THE MILLIKELVIN BARRIER IN NANOELECTRONICS

Richard Haley[1], Jonathan Prance[1] and Dominik Zumbühl[2] – DOI: https://doi.org/10.1051/epn/2021406
[1] Lancaster University, UK – [2] University of Basel, Switzerland

In labs across Europe physicists are pushing the boundaries of how far we can cool the electrons in nano-fabricated circuits and quantum-enhanced devices. The cryogen-free revolution in dilution refrigeration has liberated researchers from a reliance on helium, a costly and non-renewable resource, and hugely expanded the numbers of cooling machines available for new science and quantum technology applications which exploit the properties of materials at kelvin and millikelvin temperatures.

▲ Metal cooling islands on a nanoelectronic device (Nikolai Yurttagül, TU Delft)

While dilution refrigerator technology is developing at pace, mainly in terms of capacity and cooling power, in general commercially available base temperatures are bottoming out around a few mK. Through a combination of canny low temperature technique and careful engineering it is possible to get the electrons in on-chip devices close to these mK temperatures and make use of them. However, getting any lower, into the microkelvin regime, and demonstrating that the electrons are that cold, is a physical and technological challenge currently in the hands of a few specialist laboratories [1].

Until recently the record temperature for on-chip electrons stood at around 4mK, demonstrated in a GaAs 2D electron gas sample back in 1999 [2]. Here we look at the breakthroughs made in the last 5 years by some of the partners in the Horizon 2020 European Microkelvin Platform collaboration [3] who have finally broken the millikelvin barrier. This work has brought together researchers at Royal Holloway University of London, TU Delft, Chalmers, VTT and the authors' own institutions Lancaster University and the University of Basel.

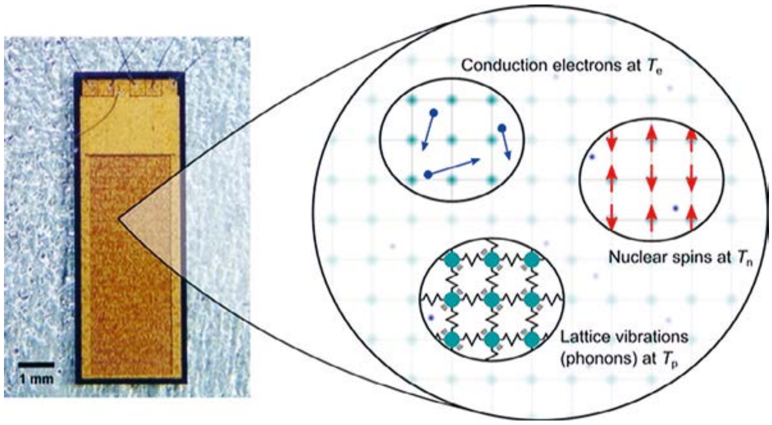
Why do we want to do this?

As well as the challenge and excitement of investigating systems in completely new regimes where new discoveries tend to lie waiting, getting electronic devices colder than the current "industry standard" of 10's of mK is becoming increasingly important for enhancing sensitivity in observing physical effects and improving the performance of quantum technologies, metrological standards and sensors. Extreme low temperature environments have inherent exploitable advantages. First, systems must be extremely well shielded against thermal and electromagnetic disturbance, which in turn enhances the signal-to-noise of systems under observation (as a guide, dilution refrigerator temperatures are orders of magnitude lower than the Cosmic Microwave Background). Second, one can utilise the low temperature behaviour of electronic materials such as conductance quantisation and superconductivity.

Colder electronic samples and devices will enable searches for new physics in a large range of systems such as topological insulators, new collective electron-spin states, 2D materials, quantum Hall, exotic superconductors and quantum phase transitions. On the technology side lower electron temperatures may prove crucial for increasing the coherence times of solid-state qubits, reducing metrological uncertainty in resistance standards and increasing the sensitivity of detectors for astrophysics and cosmology.

Why is it difficult?

Readers familiar with the frontiers of low temperature physics may be asking themselves why this is such a problem; the cooling of bulk materials deep into the microkelvin regime has been possible for decades using the textbook technique of adiabatic demagnetisation of, say, chunks of high purity annealed copper forming a "demag stage" pre-cooled by a dilution refrigerator. Others may be wondering what is so difficult for nanoelectronic devices when laser-cooled atomic gases are regularly reported in the pK and nK regimes. The challenge becomes one of asking what cooling techniques are available (lasers are not, demagnetisation is) and what problems beset nanoscale devices in remaining cold (more susceptible to nuisance heating than bulk materials, but not so fragile as gas condensates).



▲ **FIG. 1:** As the temperature of a material drops, it becomes increasingly easy to drive its internal subsystems out of thermal equilibrium. Left, an image of a Coulomb blockade thermometer [7], a device that measures its own internal electron temperature. Right, a sketch of the thermal subsystems inside its conducting parts. At millikelvin temperatures and below, the conduction electrons, crystal lattice and nuclear spins of the same material can all be at significantly different temperatures. It becomes harder to cool the conduction electrons with the refrigerator via contact with the lattice. In the device shown here the conduction electrons can instead be cooled via demagnetisation refrigeration of the nuclear spins in on-chip volumes of copper [8].

At low temperatures, the conduction electrons in a device decouple from the host lattice and, in turn, the cold chip substrate. See figure 1. At the same time the electron heat capacity reduces with temperature and exacerbates sensitivity to the many sources of parasitic heating such as radiation, electromagnetic noise and eddy currents. Ultimately the electron temperature is determined by the balance of cooling power vs parasitic heating.

Finally, one must measure the temperature of the electrons in the device, in equilibrium with the thermometer, to demonstrate that they are actually cold. This is no mean feat. The electrons are almost always at a temperature above that of the chip substrate which, in turn, will be hotter than the cold end of the refrigerator. Therefore, we choose a temperature-dependent property of the electrons themselves. Good examples are noise thermometers, the thermal properties of quantum dots, and Coulomb blockade thermometry.

How do we do it and where are we now?

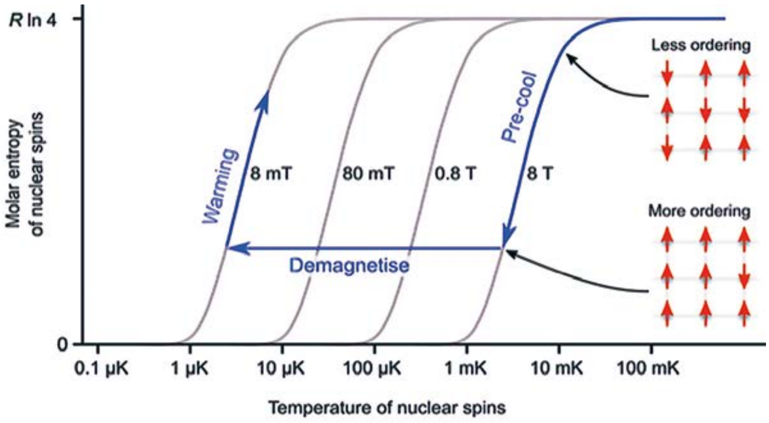
Low temperature physicists are used to exploiting high field superconducting magnets for bulk demagnetisation cooling. See figure 2. Investigating how this technique might be applied to on-chip nano-fabricated devices was something of a natural progression. Earlier records were set by using ingenious ways of transferring the cold temperatures of large demag stages “off-chip” to the conduction electrons in a device. Typically, this is done by immersing the chips and measurements leads in cold liquid helium. The challenge is to transfer the cold while ensuring the device and leads are electrically isolated from the demag stage. Royal Holloway researchers employ these methods to cool 2D electron gases [4].

The Basel team developed a completely new approach to off-chip demagnetisation by cooling each measurement lead separately with its own mini demag stage and transferring this cooling via the chip’s electrical contacts. This versatile and adaptable technique has been demonstrated in combination with modern cryogen-free refrigerators and successfully cooled 16 demagnetised measurement wires to fractions of a mK [5].

Meanwhile, VTT and Lancaster decided to deposit demagnetisation material directly on to chips and investigate whether it would cool. Serendipitously it did. The key was to add the material to a device that was also an accurate thermometer of electron temperature. Coulomb blockade thermometers made by Mika Prunnila’s team at VTT had already been shown to work down to 4 mK in an immersion cooling experiment [7]. Coating the conducting parts with copper provided a new on-chip cooling method. The total amount of copper was approximately 4 μmol, 5 or 6 orders of magnitude less than would be used in a traditional demag stage, but the thermal link between the copper and the device was essentially perfect. Starting from the base temperature of a cryogen-free dilution refrigerator and a magnetic field of 5 T, electrons were cooled from 9 mK to 5 mK [8]. The most surprising result was how long the tiny amount of copper stayed cold: just below 5 mK for up to 1000 seconds. Measurements made using a colder dilution refrigerator were able to reach 1.1 mK.

Combining both off-chip and on-chip techniques, as demonstrated in Basel [6], and also replacing copper with indium, the team led by Attila Geresdi, formerly at Delft and now at Chalmers, made a breakthrough by cooling the electrons in a Coulomb blockade thermometer below 1 mK (see Fig. 3). They realised that indium has a significantly larger cooling power than copper and this, combined with external cooling of the leads, allowed them to cool the electrons to 420 μK and keep them below 700 μK for more than 85 hours [9]. The base temperatures achievable with indium will ultimately be limited by its magnetic properties at very low temperatures and fields. Consequently, copper is capable of producing lower temperatures, but indium certainly has advantages above 400 μK.

Right now at Basel an experimental campaign is underway that combines everything we have learned so far: off-chip, on-chip and the best choices of thermometry and materials for each stage. Preliminary results indicate base temperatures around 300 μK and days-long sub-mK hold times.



▾**FIG. 2:** **Adiabatic demagnetisation cooling exploits the magnetocaloric effect where the temperature of certain materials can be changed by the application of a magnetic field. Paramagnetic indium or copper (as shown here) is pre-cooled under high magnetic field using a dilution refrigerator and superconducting solenoid. The key to the technique is to reduce the field whilst protecting the material from external heat leaks in order to follow the constant entropy adiabat as closely as possible. This can result in significant cooling of the material below the base temperature of the refrigerator.**

What next?

As well as setting new records, we have demonstrated that it is possible to cool electrons in on-chip nanofabricated devices well below temperatures currently accessible on commercial refrigerators. New tools lead to new physics, and one of the next challenges is identifying which of the new techniques is best suited for particular on-chip applications and investigations beyond those mentioned here. A key aspect of the European Microkelvin Platform

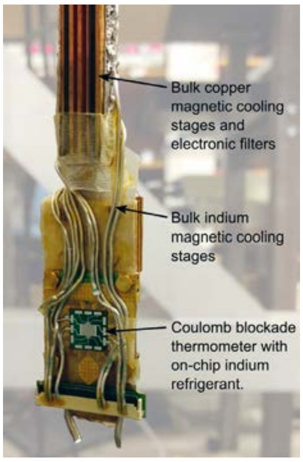


FIG. 3: The cold stage of an on-chip demagnetisation experiment at TU Delft [9]. The top of this setup attaches to the coldest part of a dilution refrigerator, which is at a temperature around 10 mK. Bulk copper and indium demagnetisation stages cool the incoming connections to the sample. Other sources of external heating are reduced by careful electronic filtering and shielding. Finally, microscopic amounts of indium on the sample itself are able to cool the on-chip electrons to temperatures close to 400 µK. Photograph by Matthew Sarsby, TU Delft.

is to bring innovation out of the laboratory and into the marketplace. Ultimately, we would like to see off- and on-chip cooling become easily accessible and cost-effective, for example as an add-on option to commercial cryogen-free dilution refrigerators. ■

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Richard Haley is a Professor of Low Temperature Physics at Lancaster University. He has interests in cooling and performing sensitive measurements on a range of systems including nano-fabricated structures and superfluid helium-3 condensates.

Jonathan Prance is a Reader in Physics and the Director of IsoLab at Lancaster University. He studies the properties of nanoelectronic structures and devices at extreme low temperatures, including quantum dots, 2D materials and superconducting circuits.

Dominik Zumbühl is a Professor of Physics at the University of Basel working on quantum transport in nanostructures studying quantum coherence, spins and interactions at low temperatures. He is also the Director of NCCR SPIN, the Swiss National Program developing spin qubits in Si and Ge.

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THE MANY FACES (PHASES) OF STRONG CORRELATIONS

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There has been considerable recent progress in discovering and understanding quantum phases and fluctuations produced by strong correlations. Heavy fermion systems are an ideal platform for systematic studies because low and competing energy scales make them highly tunable. As such the phases (faces) of strong correlations transform continuously into one another.

▲ Morphing images of the faces of Nobel laureates Heike Kamerlingh Onnes (1913) and Philip Warren Anderson (1977).

Mobile electrons in simple metals can be reasonably well described in a free electron picture – the Sommerfeld model of a Fermi gas. At the forefront of current research, however, are materials in which the electron-electron Coulomb interaction U is sizable and can not be ignored. Such "strongly correlated" materials present a wealth of phenomena that are intriguing for fundamental studies and promising for electronic applications.

Strongly correlated electrons

In theoretical descriptions, U is compared to an energy scale that relates to the kinetic energy of the electrons, typically the hopping energy t or the bandwidth W. When U/W is small, the low-energy physics of the many-electron system is described in terms of noninteracting conduction electrons, with the correlations serving as a perturbation. In other words, the conduction electrons are the only building blocks of the low-energy physics. When U/W reaches or exceeds order unity, the correlations produce new degrees of freedom – such as spins – that serve as the effective building blocks for the low-energy physics.

This applies to strongly correlated materials as exemplified by the high-temperature copper- and iron-based superconductors and heavy fermion metals. A key characteristic of these systems is that the correlations produce a plethora of quantum phases. Viewed in terms of the effective building blocks, the electron correlations are more explicitly manifested as competing interactions that promote different kinds of ground states. For example, in the 4*f*-electron-based heavy fermion metals, the *f* electrons act as localized moments of effective spin $S = 1/2$. The spins interact with a separate band of *spd* electrons through an antiferromagnetic Kondo interaction. They also couple to each other by an RKKY spin-exchange interaction, produced by the spin polarization of the conduction electrons, that is typically antiferromagnetic as well. The competing tendencies of the two interactions, to promote inter-species Kondo singlets and inter-spin singlets, respectively, lie at the heart of the heavy fermion physics.

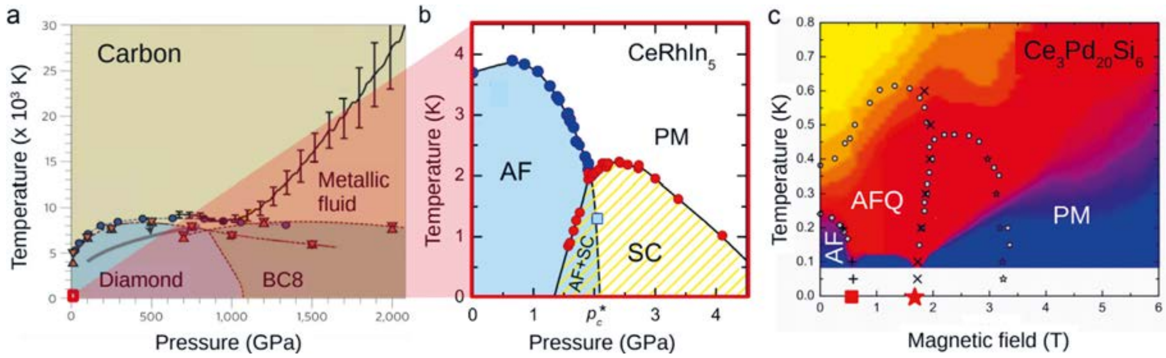


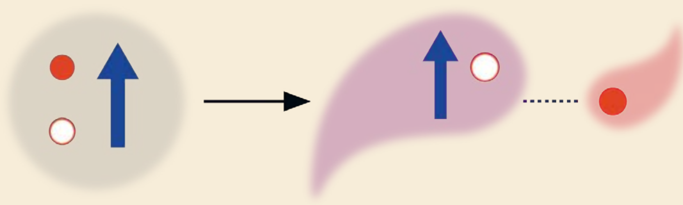
FIG. 1: Temperature-tuning parameter phase diagrams of a non-interating material (a, carbon under ultra-high pressure, BC8 is an expected metastable phase [1]) and two strongly correlated materials (b, $CeRhIn_5$ [2] and c, $Ce_3Pd_{20}Si_6$ [3]). The tunability is vastly enhanced in strongly correlated materials as seen from a comparison of the scales of panels a and b. Red colour in c represents linear-in-temperature resistivity.

Quantum criticality

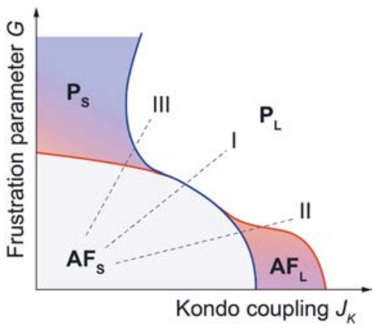
In many of these materials non-thermal control parameters such as pressure or magnetic field can tip the balance between the different interactions. As a consequence, a given phase can be suppressed and another one stabilized as function of a control parameter (Fig. 1). When this process occurs continuously down to the absolute zero in temperature, the ensuing zero-temperature *quantum* phase transition is a quantum critical point (QCP). It separates distinct phases, for instance an antiferromagnet (AF) from a paramagnet (PM). The QCP anchors quantum critical fluctuations which can strongly affect the finite temperature properties of the material. A well-known example are electrical resistivities with unusual temperature dependences, most notably the linear-in-temperature "strange metal" behaviour. This is seen to emerge from two magnetic-field tuned QCPs in the heavy fermion compound $Ce_3Pd_{20}Si_6$, at the border of phases with AF and antiferroquadrupolar (AFQ) order, respectively (Fig. 1c). Another intriguing effect is that quantum critical fluctuations can stabilize new phases. For instance, in the heavy fermion compound $CeRhIn_5$, a phase of unconventional superconductivity (SC) is stabilized as an AF phase is continuously suppressed to zero by pressure (Fig. 1b).

An overall understanding of heavy fermion quantum criticality comes in the form of a global phase diagram (Fig. 2). The Kondo interaction J_K promotes quantum fluctuations. The ensuing Kondo effect leads to a ground state in which the local moments form a spin singlet with the conduction electrons. It converts the local moments into electronic excitations, the composite heavy fermions (Box). The latter hybridize with the conduction electrons, and the Fermi surface expands and is called large (subscript L in Fig. 2). At smaller J_K, the local moments establish antiferromagnetic order from the dominating RKKY interaction. They form spin singlets among themselves, which destabilizes the inter-species Kondo singlets. With this Kondo destruction [3], the Fermi surface is formed by the conduction electrons alone and is called small (subscript S in Fig. 2). The RKKY interaction also promotes quantum fluctuations, which can be enhanced by geometrical frustration *G*. The global phase diagram captures the effect of both types of quantum fluctuations. Importantly, it goes beyond the Landau framework where quantum critical fluctuations derive uniquely from the suppression of the order parameter as the broken-symmetry phase (AF in our case) gives way to a paramagnetic phase (P). Here, in addition to the Landau order parameter, the Kondo effect and its destruction characterize the quantum phases and fluctuations.

Experimentally, the change of the Fermi surface across such a Kondo destruction QCP was evidenced by Hall effect measurements [3]. Associated with this transition is the strange metal linear-in-temperature electrical resistivity referred to above. In addition, a recent optical conductivity investigation in the THz range – appropriate to probe the low energy scales of heavy fermion systems – revealed quantum critical charge fluctuation. The result indicates that fermionic degrees of freedom, in addition to the bosonic order parameter fluctuations, govern the quantum criticality [4]. This is exactly the behaviour expected in a Kondo destruction QCP. Similar phenomena have also been observed in other classes of strongly correlated electron systems, most notably the high-temperature cuprate superconductors [5,6]. The common features raise the exciting possibility that high-temperature superconductivity is an emergent phase stabilized by the type of quantum criticality that goes beyond the order-parameter-fluctuation paradigm.



Ground state (left) and elementary excitations (right) of a strongly interacting system described by the Kondo effect. The spin singlet formed between a local moment (blue arrow) and conduction electrons (red dots) supports excitations in the form of a composite heavy quasiparticle (large tadpole) that hybridizes with the conduction electrons.



◄ **FIG. 2:** Theoretical phase diagram of AF Kondo lattice models [3]. The different quantum phases are described in the text. The paths I, II and III represent different tuning trajectories that realize distinct sequences of quantum phase transitions and the associated QCPs. This global phase diagram provides a framework to guide the exploration of heavy fermion compounds with different spatial dimensionality or lattice geometry, which may realize the different regimes of the parameter space.

Correlation-driven electronic topology

Another area of recent developments concerns the combination of strong electron correlations and nontrivial electronic topology. Topological states are of interest because they are imprinted in a material for symmetry reasons. As such they are expected to be robust against disorder. This makes topological materials candidates for new electronic devices. Topological phases are inherently not characterized by a (Landau) order parameter. To delineate their boundaries and devise global phase diagrams as described above for (topologically trivial) strongly correlated electron systems requires to produce correlated topological states, identify their characteristics, and tune them by external parameters.

An interesting recent discovery is that strong correlations can lead to giant topological responses. A new state of matter, dubbed Weyl-Kondo semimetal, was shown to exhibit thermodynamic and electrical transport signatures that overshoot expectations for their non-interacting counterparts by orders of magnitude [3] (Fig. 3). In addition, topological features in strongly correlated systems are much more readily controllable by external parameters than in the non-interacting case. These two features will help to identify and tune topological phases and thus map out their global phase diagrams. This in turn will allow to reveal the underlying principles. Whether quantum critical fluctuations can also promote emergent topological phases – in analogy with unconventional superconductivity for topologically trivial systems – is an exciting question for future studies. The observation of quantum criticality, with characteristics of Kondo destruction, in a candidate Weyl-Kondo semimetal certainly nourishes this hope [7].

Outlook

We have only been able to give a few examples of the considerable recent progress in the field of strongly correlated quantum materials. Other directions that are actively being explored include the investigation of phases governed by building blocks beyond simple spins and conduction electrons, enhanced frustration or hybrid interactions. In addition to the multitude of strongly correlated materials classes, artificial structures such as twisted bilayer systems are now available and hold promise for studies of correlation physics via moiré potentials. For further reading we refer the reader to [3]. Finally, new experimental techniques, for instance measurements at ultralow temperatures [9] or the growth of quantum critical heavy fermion compounds by molecular beam epitaxy [4], open entirely new possibilities. One of the grand challenges to attack is to exploit the rich physics of correlated quantum materials for quantum devices. With their strongly amplified responses, the prospect is certainly high. ■

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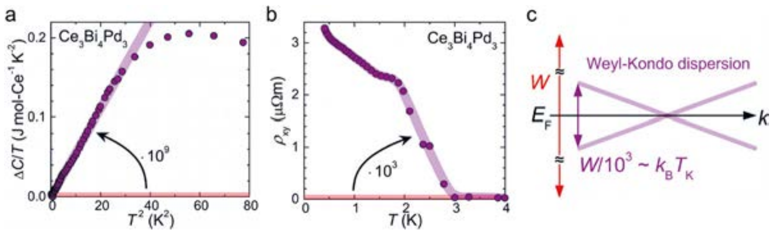

▲ **FIG. 3:** Giant topological responses of the Weyl-Kondo semimetal $Ce_3Bi_4Pd_3$ [3,8]. The giant slope of the electronic specific heat coefficient $\Delta C/T$ as function of T^2 (a) derives from linearly dispersing electronic bands, the width of which is strongly renormalized by the Kondo effect (characterized by the Kondo temperature T_K) with respect to the width of the underlying non-interacting band W (c). The giant spontaneous Hall resistivity ρ_{xy} (b) is attributed to Berry curvature divergences at the Weyl nodes which, in a Weyl-Kondo semimetal, are situated in close vicinity to the Fermi level. Electronic transport is therefore very strongly affected by the associated fictitious magnetic monopoles in momentum space.

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