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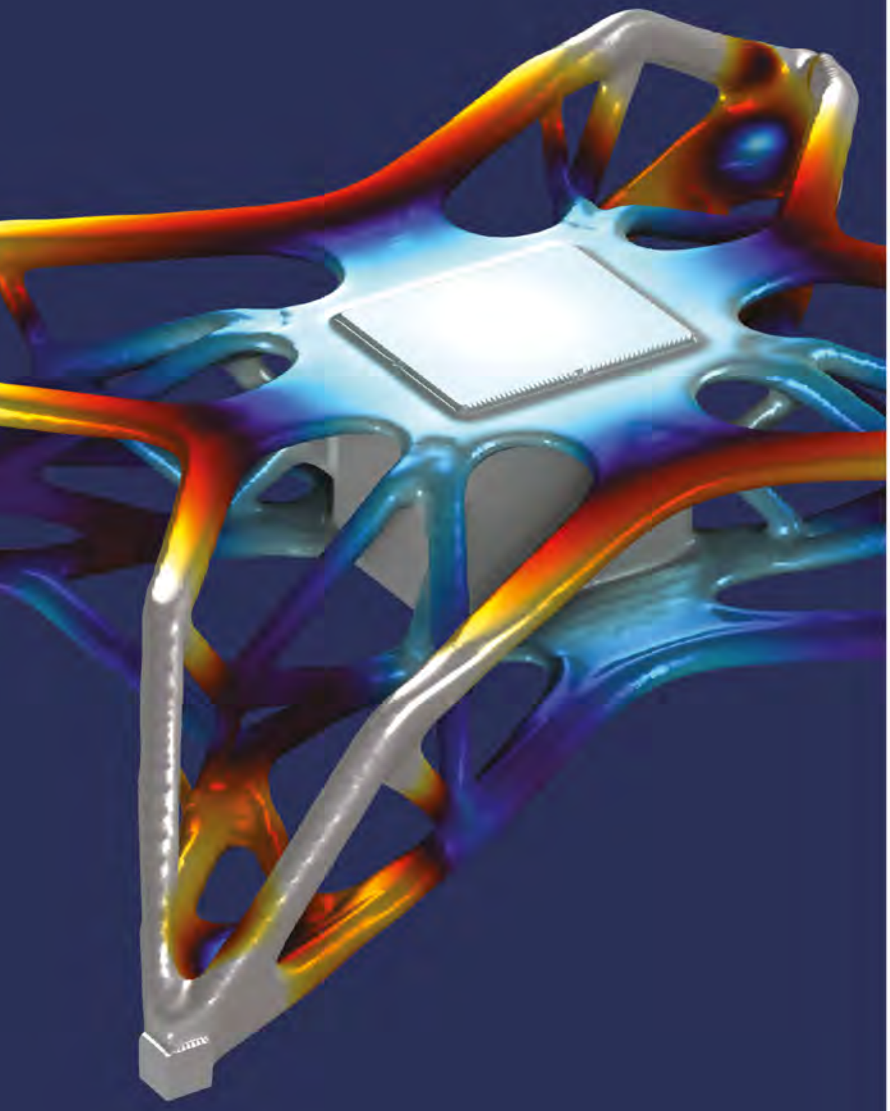

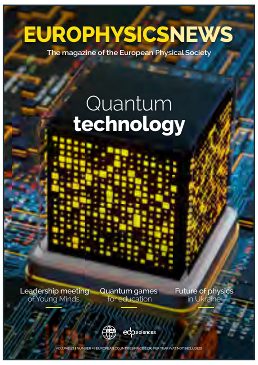

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Cover picture: Artist's impression of a future processor of a quantum computer.
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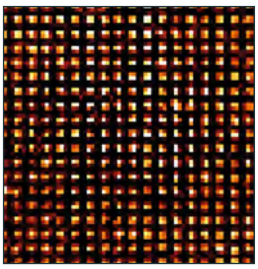

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Quantum simulation and computing

[EPS EDITORIAL]

The EPS Forum 2022: This is done!

Between June 2 and 4, 2022 the European Physical Society (EPS) held its first Forum at the International Conference Center of Sorbonne University in Paris. How good it was to all meet face-to-face in the city of light under a pleasant sunshine!

Prepared for more than a year with 75 representatives of the EPS Member Societies, Divisions and Groups, Associate Members and the EPS Secretariat, the Forum welcomed almost 500 participants among whom 184 students coming from 30 different countries, from Europe of course, but also from India, South America, and even Singapore.

The format of the EPS Forum included a series of conferences, round tables and workshops on the following topics: Energy and sustainability, accelerators, high-energy particle physics, nuclear physics, quantum technologies and photonics, machine learning and artificial intelligence, biophysics, technological sequencing of biomolecules and human health, condensed matter physics – from quantum materials to additive manufacturing. The detailed programme is still accessible online (www.epsforum.org), while a short video can be viewed from the link: www.youtube.com/watch?v=McU8Vz2okAI.

The Forum's objective was to showcase the latest developments in these fields of physics, both from their potential links with the industry and from the most recent achievements in fundamental science. The EPS Forum dedicated two days for each of these goals. Thursday June 2nd hosted the event "physics meets industry" that fostered direct exchanges between a majority of master, PhD students, postdocs and stakeholders of physics-based industrial companies. This first day was opened by a plenary conference given by Mariya Gabriel, European Commissioner for Innovation, Research, Culture, Education and Youth about filling the gap between science and innovation. More than 60 young researchers could present the results of their research during a long poster session.

Friday June 3rd hosted a scientific colloquium highlighting the latest discoveries in physics. The morning session welcomed three laureates of the Nobel prize in Physics: Prof. Barry Barish from Caltech, USA, Prof. Serge Haroche from École Normale Supérieure & Collège de France in Paris, and Prof. Michael Kosterlitz from Brown University, USA. All along the day, several round tables also discussed various societal topics, such as the European Research Council (ERC) and Widening Participation of Eastern and Southern States, for which Andrzej Jajszczyk, ERC Vice-President for physics, was invited to give a talk.

In parallel to these two days, three hands-on sessions and one masterclass trained students on quantum computing and scientific writing, while the patio of the Conference Center housed 25 stands that allowed fruitful exchanges with young graduates looking for job opportunities. The third day, Saturday June 4th, hosted the regular business meeting of the EPS Council, open to the Council Delegates.

In addition, the EPS Young Minds held a very successful Leadership Meeting (read the following article). 25 representatives from the International Association of Physics Students (IAPS) and 25 others from the 5 Universities of the 4Eu+ Alliance were moreover invited by the EPS to enjoy the different sessions of the Forum. Some of them helped the EPS secretariat to carry out logistical arrangements and we are very grateful to these student helpers.

More than 70 research organisations, industrial groups and learned societies financially contributed to this event. Their generous support helped the EPS to provide accommodation and meals to nearly 150 student attendees. All the people who made the Forum could finally enjoy a nice cruise and a pleasant dinner on the Seine.

In summary, this first edition of the EPS Forum demonstrated that all the EPS bodies can work together over a year in order to promote the young generation of European physicists, to bridge the gap between academic research and industry, and to advertise the latest developments in fundamental physics at the highest level.

Installing this event over time is the next challenge for the EPS. A survey was sent to the participants to collect their opinions and possibly improve the next editions of the Forum. We will publish the results of this survey in the next issue of EPN.

Waiting for this, I here renew all my warmest thanks to all the organisers and programme committee members of the first EPS Forum. ■

■ **Luc Bergé,** *EPS President*

EPS Young Minds - an outlook in 2022

The Young Minds (YM) programme of the European Physical Society (EPS) was initiated 12 years ago, with the goal to connect young students and researchers all over Europe, to strengthen their collaboration, the exchange among them, and to support their professional and personal growth. The program now comprises more than 60 active sections operating in over 35 countries within Europe and the neighboring Mediterranean countries.

Richard Zeltner and Mattia Ostinato

The EPS YM Leadership Meeting 2022

A highlight in the annual agenda of YM is the annual Leadership Meeting (LM) during which section delegates from the whole network are coming together to engage in various professional development and networking activities. Due to the Corona pandemic the LM 2020 had to be cancelled and the LM 2021 has been organized as a virtual event. In 2022, with the pandemic situation being more under control, the YM community gathered for its first physical LM since 3 years ago in the framework of the EPS Forum 2022, from June 2 to 3 at the Sorbonne University in Paris. The co-location with the EPS Forum allowed the participants to benefit from both the professional development and networking opportunities which are provided during the LM and from the exposition to industrial technology leaders and world-class researchers, including 3 Nobel Laureates, that presented at the Forum. The meeting gathered 43 section delegates, coming from 21 different countries, as well as guests from the "International Association of Physics Students" and other young researchers not yet related to EPS YM. This meeting can therefore be considered as a great success.

The Leadership Meeting was opened on June 2 by welcoming words of Richard Zeltner, EPS YM Chair, and Mattia Ostinato, Action Committee Member and lead of the LM organization team. After the participants formed a first connection during a Physics Quiz, they attended the various industrial talks, which provided insights into the career opportunities and the research carried out in the private sector. In the afternoon of the first day Dr. Jean-François Morizur,

▼ The EPS Young Minds leadership meeting during the EPS Forum 2022 in Paris.

Co-Founder and CEO of Cailabs, provided a "From PhD to CEO" seminar. In this session, which was moderated by Yann Amoroux from the European office of Optica, Dr. Morizur shared his entrepreneurial experiences as co-founder and CEO.

A unique meeting: Nobel Laureate and professional development talks

Day two kicked off with the Nobel Laureate session, during which the Young Minds attended talks from Prof. Barry Barish, Prof. John Michael Kosterlitz, and Prof. Serge Haroche. The following slot was dedicated to professional development: First, Dr. Giuliana Galati, University of Bari, Aldo Moro, INFN, provided a seminar on "Science Outreach and Mass Media" during which she discussed the importance and compromises of bringing research to the general public. Second, addressing the questions that can come up for young researchers when making career decisions, Prof. Petra Rudolf provided an insightful talk on "The landscape of career tracks for graduates in Physics", equipping the Young Minds with the knowledge and tools to make qualified and informed decisions.

The professional development slot was followed by a short and interactive workshop during which members of the Action Committee joined the participants to form small workgroups, working out what the sections expect from the Young Minds Programme and how the programme goals can be even more efficiently achieved in the future. Finally, day two concluded with the Young Minds poster session. Many section delegates used the opportunity to present a summary of their recent section activities, making the session a great hub for the exchange of ideas and mutual inspiration.

The large number of participants, many of them coming from outside the YM network, the great talks provided by the invited speakers, the co-location with the EPS Forum, and the lively and insightful discussions that took place over the two days made the LM 2022 a very special experience for the YM network and we are very much looking forward to the 2023 edition.

Mattia Ostinato elected new chair of EPS Young Minds

Traditionally, the Action Committee uses the Leadership Meeting to gather for its annual meeting, discussing the activities and events of the previous year and planning the year ahead. Since the two-year tenure of Richard Zeltner ended in June 2022, an election for the new YM Chair was held during which Mattia Ostinato, former member of the YM section in Naples, was elected YM Chair for the period 2022 to 2024. Among others topics and very much aligned with the vision of EPS YM his agenda includes working towards more national and international intersectional communication and collaboration. ■

Trans-Atlantic Partnership for Enhancing Scientific Careers in Developing Countries

The American Physical Society (APS), the European Physical Society (EPS) and the International Centre for Theoretical Physics (UNESCO-ICTP), in honor of the International Year of Basic Science for Sustainable Development (IYBSSD 2022), have announced the initiation of the joint APS-ICTP-EPS Travel Award Fellowship Programme (ATAP).

Washington, Mulhouse, Trieste, 29 August 2022 — The American Physical Society (APS), the European Physical Society (EPS) and the International Centre for Theoretical Physics (UNESCO-ICTP), in honor of the International Year of Basic Science for Sustainable Development (IYBSSD 2022), announce the initiation of the joint **APS-ICTP-EPS Travel Award Fellowship Programme (ATAP).** ATAP is aimed at active early career scientists from developing countries, supporting short-term research visits to laboratories in Europe and North America. This programme grants the major costs of two-month visits for young scientists, up to $5,000. Applicants just need to send their complete CV including publications, at least one letter of reference, a letter of agreement and endorsement from the host laboratory and a 1-page budget management plan evaluating the travel and local expenses. The materials must be sent to itlabs@ictp.it by 28 February in the year of the intended Fellowship.

The goal of ATAP is to enable selected recipients to strengthen opportunities to conduct world-class research, and establish collaborations to enhance their scientific careers. The recipients may return to the laboratories of their alma mater to use laboratory facilities they are familiar with and re-connect with colleagues.

We are happy to announce the selected recipients of the 2022 ATAP programme:

Dr. Azam KARDAN, Damghan University, Iran, who will spend two months at the MAX IV Laboratory of Lund University, Sweden, to work with Profs. Martin Bech and Pablo Villanueva Perez on tomographic acquisitions using machine learning;

Dr. Llinersy URANGA PINA, University of Havana, Cuba, going to the University Paul Sabatier in Toulouse, France, where she will work with Prof. Dr. Christoph Meier and Dr. Nadine Halberstadt on materials science;

Dr. Ausama Ismael KHUDIAR, Institute of Materials Research/ Department of Sciences and Technology of the Ministry of Higher Education and Scientific Research, Republic of Iraq, who will go to the Eberhard Karls Universität in Tubingen, Germany, to work with Dr. Nicolae Barsan on gas sensors.

CONTACT:
Joe Niemela, niemela@ictp.it ■

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A SUBNANOMETRIC MATERIAL REVEALS NEW QUANTUM-CHEMICAL INSIGHTS INTO SURFACE POLARONS

María Pilar de Lara-Castells and Salvador Miret-Artés – DOI: https://doi.org/10.1051/epn/2022401
Instituto de Física Fundamental, CSIC, Serrano 123, 28006 Madrid, Spain.

The recent advent of cutting-edge experimental techniques allows for a precise synthesis of monodisperse subnanometric metal clusters composed by just a few atoms, and opens new possibilities for subnanometer science. The decoration of titanium dioxide surfaces with Ag_5 atomic clusters has enabled the stabilization of surface polarons and provided new quantum-chemical insights into an electron polarization phenomenon revealed by their formation.

The very recent development of highly selective experimental techniques enabling the synthesis of subnanometer metal clusters with high monodispersity is pushing our understanding of these, more "molecular" than "metallic", systems far beyond the present knowledge in materials science. When the cluster size is reduced to a very small number of atoms (less than 10), the *d*-band of the metal splits into a subnanometric network of discrete molecule-like *d* orbitals, with the inter-connections having the length of a chemical bond (1–2 Å). The spatial structures of these molecular orbitals make all of the metal atoms cooperatively active, leading to novel properties particularly interesting in nanotechnology including luminescence, sensing, bioimaging, theranostics, energy conversion, catalysis, and photocatalysis. For instance, new catalytic and optical properties are acquired by titanium dioxide (TiO_2) surfaces when decorated with Cu_5 atomic clusters: [1–3]. The Cu_5 clusters shift the material's absorption profile towards visible light, where the sun emits most of its energy [1]. The coated titanium dioxide stores the absorbed energy temporarily in the form of charge pairs, *i.e.*, electrons and holes, in the direct vicinity of the surface. This is a perfect setting for surface chemistry.

Seeking further applications, the TiO_2 surface was decorated with atomic silver clusters, Ag_5 [4,5]. In fact, the coupling with light is expected to be more effective in the silver-modified material. By doing this we uncovered new relevant fundamental insights into a polarization phenomenon accompanying the formation of surface polarons [4].The results from this work are summarized in this contribution.

Surface polaron formation and Ag_5–induced stabilization

The polaron concept, first proposed by Landau and Pekar (see Refs. 6, 7), characterizes an electron moving in a dielectric crystal such as titanium dioxide (TiO_2). Defects on TiO_2 surfaces such as oxygen vacancies lead to excess electrons that become localized in Ti^{3+} $3d^1$ states, as illustrated in panel A of Figure 1. In order to screen the localized Ti^{3+} $3d^1$ electron, the O^{2-} anions depart from their equilibrium positions, as indicated with red arrows in the enlarged view of panel A of Figure 1. This lattice distortion is known as the phonon cloud, and the entity formed by the Ti^{3+} $3d^1$ electron and its associated phonon cloud is the polaron. Furthermore, the electron also carries a polarization cloud which modifies the electronic structure in its vicinity, characterizing a polarization phenomenon associated with the formation of a surface polaron [4,5].

Surface Ti^{3+} cations hosting polarons are easily oxidized, so their formation is more favourable at •••

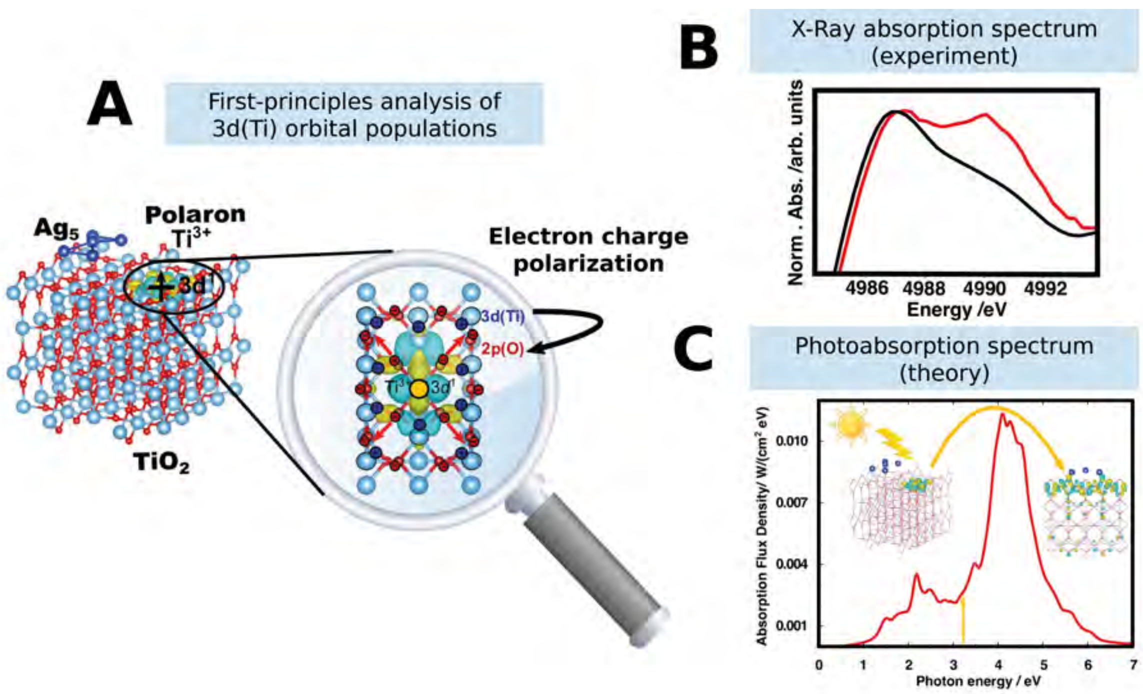
subsurface TiO_2 layers [4,5]. A way to stabilize surface polarons is via the deposition of subnanometric silver (Ag_5) clusters [4]. The first step of the Ag_5–induced surface polaron formation is the donation of an unpaired electron from Ag_5 to the TiO_2 surface. As shown in panel A of Figure 1, the donated electron becomes localized in one specific 3*d* orbital lying at the surface, centered at the Ti atom right below the Ag_5 cluster. After receiving this extra electron, the Ti^{4+} cation becomes a Ti^{3+} cation. As indicated with red arrows in the enlarged view of panel A of Figure 1, the formation of this Ti^{3+} $3d^1$ polaronic state is correlated with the outward movement of the neighboring oxygen anions. The attractive electrostatic interaction between the localized Ti^{3+} $3d^1$ electron and the positively charged Ag_5 cluster favours the stabilization of the Ag_5–induced surface polaron. The pair formed by the polaronic charge and the positively charged silver cluster could ease surface redox chemistry.

Evidence of the surface polaron-induced electron polarization phenomenon

As illustrated in Figure 1, the evidence for the electron polarization phenomenon has been found in three different ways as follows [4]:

1) Our first-principles analysis has provided evidence for the Ag_5–induced depopulation of 3*d*(Ti) orbitals, typically in favour of 2*p*(O) orbitals, despite the fact that polarons are characterized by an excess charge (*i.e.*, "extra" electrons) trapped at the Ti sites hosting them.
2) A second evidence of the depopulation of 3*d*(Ti) orbitals in favour of 2*p*(O) orbitals has been found through X-ray absorption near edge structure (XANES) spectroscopy. This technique is characterized by a high chemical selectivity. Panel B of Figure 1 shows the XANES spectra at the Ti K-edge of bare TiO_2 nanoparticles (shown in black) and Ag_5–modified TiO_2 nanoparticles (shown in red). The increase of the spectral feature appearing at ca. 4990 eV for Ag_5–modified TiO_2 nanoparticles indicates a charge transfer from Ti cations to O anions, which results in an on average decrease of the 3*d*(Ti) orbitals population.
3) Moreover, a first-principles simulation of the UV-Vis optical response of the surface polaron provided further insights into the correlation between the depopulation of the 3*d*(Ti) orbitals and the polaron formation as follows: the excitation of the Ag_5–TiO_2 system with a photon energy at the end of the visible region causes the "jump" of the polaron Ti^{3+} $3d^1$ electron to the 3d orbitals of the surface Ti atoms that have suffered depopulation. Hence, the polaron induces a hole (lack of one electron) which is extended over the surface Ti atoms in its vicinity and this hole becomes filled upon photo-excitation of the polaron. The photo-absorption spectrum is calculated by weighting the absorbance of the system with the solar flux [4] (*i.e.*, the absorption of solar energy). It is shown in panel C of Figure 1, together with the jumping of an electron from the polaron Ti^{3+} $3d^1$ state to an acceptor state formed by many surface 3*d*(Ti) orbitals.

▾ **FIG. 1:** a) Figure illustrating the formation of a surface polaron as a localized $3d^1$ electron, and an enlarged view illustrating how the Ti^{3+} $3d^1$ electron repels nearby oxygen ions while attracting nearby titanium cations, which, in turn, affects the local electronic structure and causes an electron charge polarization phenomenon. b) X-ray absorption spectrum at the Ti K-edge of bare TiO_2 (black line) and Ag_5–modified TiO_2 nanoparticles (red line). c) Theoretical UV-Vis spectra showing how the polaronic Ti^{3+} $3d^1$ state is modified when exciting it with a photon energy of about 3.1 eV (marked with a yellow arrow) [4].



The mechanism responsible for the average depopulation of $3d$(Ti) orbitals in favour of $2p$(O) orbitals in the presence of a surface polaron can be explained as follows: the localized Ti^{3+} $3d^1$ electron repels nearby oxygen anions and attracts nearby titanium cations which, in turn, affects their electronic structures, causing the transfer of electronic charge from Ti^{4+} cations to O^{2-} anions (see panel A of Figure 1).

Summarizing, the TiO_2 surface modification with the atomic cluster Ag_5 has served to disclose a new way of stabilizing surface polarons, and to reveal a polarization phenomenon associated with surface polaron formation. This polarization phenomenon arises from quantum-chemical effects and, particularly, electron charge transfer processes induced by the unpaired electron of the adsorbed subnanometric Ag_5 cluster. The exploration of the internal structure of the polarons has been achieved by combining state-of-the-art first principles theory with XANES spectroscopic measurements.

Our findings are expected to contribute not only to an improved fundamental understanding of surface polarons but also to the controlled formation of, *e.g.*, two-dimensional polaronic materials [5] and usage in applications. Our very recent studies [1–5] thus confirm the great potential that lies in this new class of materials, which are shaping the modern field of subnanometer science. ■

About the Authors

María Pilar de Lara-Castells is a senior researcher at the Institute of Fundamental Physics (IFF-CSIC) and was invited full professor at Université Paris-Est Marne-la-Vallée (2011 and 2014). At present, she coordinates a National Project (AEI, Ref. PID2020-117605B-I00), and is the main proposer of the COST Action CA21101 "Confined molecular systems: from a new generation of materials to the stars" (COSY).

Salvador Miret-Artés is full professor and director of the Institute of Fundamental Physics (IFF) in the Spanish National Research Council (CSIC).

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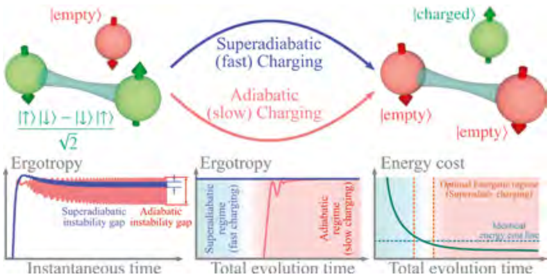
Superadiabatic Quantum Batteries

Recent advances in quantum thermodynamics and control theory have broadened the horizon ahead of us, leading to the development of new quantum technologies. In this context, a remarkable quantum device allows us to exploit the properties of quantum systems to efficiently store energy.

This device is known as a quantum battery (QB). QBs are expected to provide energy to realize work. The maximum energy that can be extractable as work from a quantum system via unitary operations is called ergotropy. The search for reliable and efficient sources of ergotropy has motivated the community to look at a diversity of physical systems. Although QBs are a quantum analog to conventional (classical) batteries, it is evident the discrepancy between the features of classical and quantum batteries. In particular, the charging stability is a characteristic that needs to be perfectly controlled for QBs, what can be achieved through a suitable adiabatic approach. Adiabaticity is a convenient tool in quantum control to drive the system to a target state, but it may require long evolution times. Our work provides a route to achieve such a controllability in high-speed charging QBs through shortcuts to adiabaticity (STA).

By using a system composed of a pair of entangled quantum bits (qubits) working as a QB and an auxiliary qubit working as a consumption hub, we first proposed the use of both entangled Bell states and adiabatic dynamics to provide a novel kind of stable and power switchable QBs. However, due to fundamental limitations of the evolution speed imposed by the validity conditions to adiabaticity, the performance of such a device would be, in principle, drastically affected by undesired interactions between the battery and its surrounding environment. In adiabatic QBs, the charging power is constrained by the total evolution time τ_{ch} required to adiabatically drive the system from an empty battery state to a fully charged one. If we take into account decoherence processes, a second time scale τ_{coh}, associated to the coherence time of the system, needs to be considered and the condition $\tau_{ch} << \tau_{coh}$ must be held for any powerful and highly efficient adiabatic QB. In this scenario, strategies to speed up the adiabatic charging process are more than welcome, circumventing the decoherence effects on the QB. In this regard, STA schemes are highly efficient for speeding up the charging process while keeping the stability property intact, since we perfectly mimic the adiabatic dynamics. One could highlight two main contributions of the current work: i) the introduction of local and global stability conditions for QBs, and ii) the proposal of a *Superadiabatic* QB. In short, *local* stability states that, when the battery is connected to a charger or consumption hub, the energy transferred remains around the maximum ergotropy for a finite amount of time Δt. When $\Delta t \to \infty$, the local stability gives place to the *global* one. In the real world, the regime $\Delta t \to \infty$ is never achieved due to decoherence effects, then we can consider the weaker condition $\Delta t \approx \tau_{coh}$, instead. In addition, from an energy spending point of view, we further compared the adiabatic and superadiabatic models as well. This analysis reveals that, through an adequate choice of the speed charging, a superadiabatic QB leads to a significant power enhancement concerning its adiabatic counterpart if we provide a (small) additional amount of energy resource. The definitions and results discussed in the referred study opens a broad avenue to the development of alternative ways to build stable and powerful QBs. ■



▲ Top: Sketch of the initial and final state of the QB-consumption hub (or charger-QB) system, where adiabatic and superadiabatic strategies can be used to a same purpose (energy transfer). Bottom: Representative graphs showing the expected advantage of superadiabatic QB concerning its adiabatic counterpart.

We would like to thank to Almir Herisson Costa dos Santos, from Federal University of Cariri, for his help in sketching the figure. A.C.S. acknowledges the financial support of the São Paulo Research Foundation (FAPESP) (Grants No. 2019/22685-1 and 2021/10224-0). M.S.S. acknowledges financial support from the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (No. 307854/2020- 5). This research is also supported in part by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (Finance Code 001) and by the Brazilian National Institute for Science and Technology of Quantum Information [CNPq INCT-IQ (465469/2014-0)].

■ Alan C. Santos, Andreia Saguia and Marcelo S. Sarandy

Defining our quantum future: experts call for diversity and collaboration

Oxford Instruments NanoScience, in partnership with the Quantum Insider, has recently launched the Quantum Technology | Working in Quantum video series. At the heart of this series is the recognition that the successful commercialisation of quantum must involve a far-reaching commitment to diversity and collaboration from industry, government, and academia.

Rapid commercial growth for the industry will, in part, come down to its people: considerable hires are needed to combat the skills shortage in the sector. A common industry myth, which says that you need a quantum-specific PhD to pursue a quantum-related career, is hampering this growth. Richard Moulds, General Manager of Braket, Amazon's quantum computing service, emphasises the restraint this misconception imposes on the wider industry. Moulds's simple philosophy is increasingly becoming a hallmark of the thinking of industry frontrunners: 'the more people who can get their hands on the technology, experiment with and experience it, the faster we, as a community, can innovate' and ultimately, the faster we can develop 'a global functioning quantum infrastructure that millions of people can use and participate in'.

For quantum to progress, especially commercially, a mix of experts and perspectives are required. This list might include, but is not limited to, software engineers and data scientists, chemists and biologists, and those with business and communication skills. Electricians and plumbers too, who are curious about the practical challenges posed by quantum engineering, have a crucial role to play in pushing the industry forward. In other words, the industry needs people who are curious about the way their car or computer works, as much as it needs trained quantum physicists.

Quantum's problem-solving capabilities for the world's greatest challenges are well-documented. The need for diverse teams, however, goes beyond just ensuring technical success; it has ethical implications too. Experts suggest we are approaching a watershed moment, in that those developing quantum technology today will determine industry partners and markets for the future. It is essential then that the collaborative networks which drive the industry forward are as diverse as possible to shape a future in which everyone can thrive. UKQuantum, in line with this objective, is on a mission to 'unite the … industry with one voice' – the success of which will be determined by that industry's ability to represent society at large.

Tech tycoons with a variety of vantage points, ranging from academia to industry have recently discussed how failing to cultivate a diverse chorus of voices – and to encourage people from under-represented backgrounds to apply for quantum careers – will result in a technological future which reproduces damaging biases. In light of this attitude, symposiums, workshops, and even quantum summer schools – at Bristol University in the UK, Radboud University in the Netherlands and the Qiskit global summer school developed by IBM – are attracting new talent and connecting thinkers across the quantum landscape. The UK government's Department for Business, Energy & Industrial Strategy is currently developing a 'Quantum Strategy' informed by experts from across the private and public sectors.

Working in Quantum emphasises the common message connecting these initiatives: the recognition that the free exchange of knowledge and minds, interdisciplinarily and internationally, will facilitate a future where the full force of quantum's benefits can be unleashed. While quantum's place in the world seems inevitable, it is now not only what, but who, will define our quantum future. ■

Working in Quantum video series: https://thequantuminsider.com/2022/08/16/working-in-quantum-series-brings-together-the-industry-to-call-for-diversity-and-collaboration-in-quantum/

https://nanoscience.oxinst.com/working-in-quantum

TechUK and QED-C in conversation with Stuart Woods, managing director of Oxford Instruments NanoScience: https://www.linkedin.com/pulse/why-quantum-needs-diversity-what-we-can-do-achieve-stuart-woods/?trackingId=P38ftZX9T4KYT6fvmwhbsQ%3D%3D

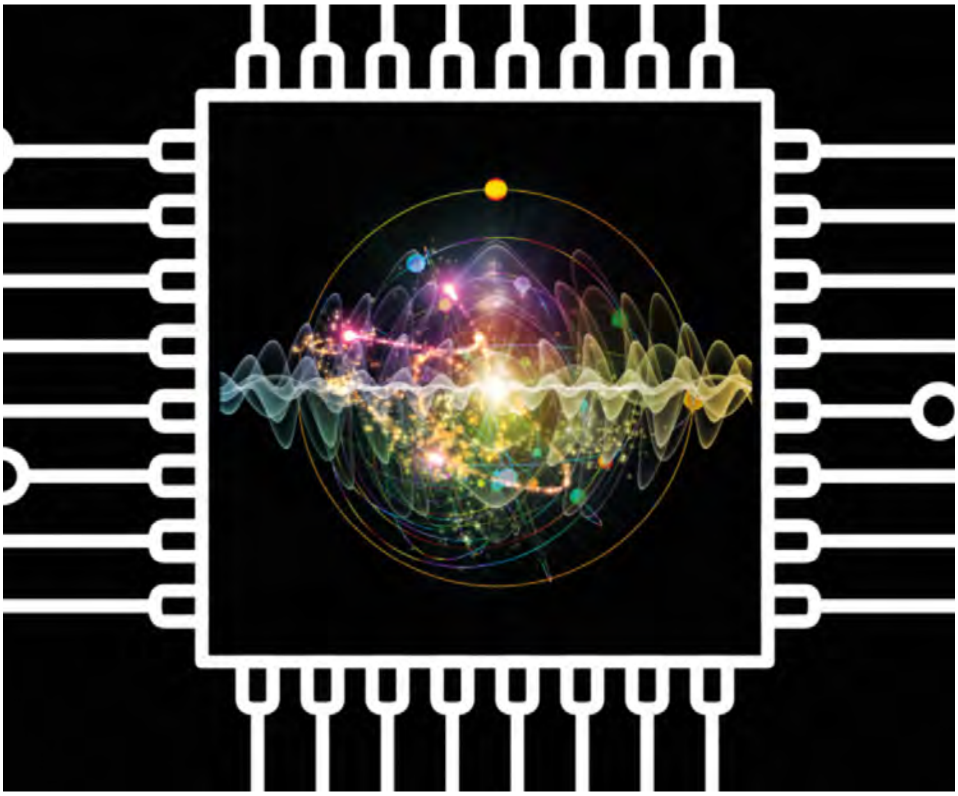
Authored by Stuart Woods, Managing Director, Oxford Instruments NanoScience.

Quantum control for advanced technology: Past and present

Quantum devices are a promising technological advance for the future, but this will hinge on the application of quantum optimal control top real-world devices. A new review looks at the status of the field as it stands.

One of the cornerstones of the implementation of quantum technology is the creation and manipulation of the shape of external fields that can optimise the performance of quantum devices. Known as quantum optimal control, this set of methods comprises a field that has rapidly evolved and expanded over recent years.

A new review paper published in EPJ Quantum Technology and authored by Christiane P. Koch, Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin along with colleagues from across Europe assesses recent progress in the understanding of the controllability of quantum systems as well as the application of quantum control to quantum technologies. As such, it lays out a potential roadmap for future technology.



▲ A new review lays out a roadmap for quantum technologies. Credit: Robert Lea

While quantum optimal control builds on conventional control theory encompassing the interface of applied mathematics, engineering, and physics, it must also factor in the quirks and counter-intuitive nature of quantum physics.

This includes superposition, the concept that a quantum system can exist in multiple states at one time, one of the keys to the advanced computing power of machines that rely on quantum bits—or qubits.

Ultimately the main goal of quantum optimal control is to make emerging quantum technologies operate at their optimal performance and reach physical limits.

"Each device architecture comes with specific limits but these limits are often not attained by more traditional ways to operate the device," Koch says. "Using pulse shaping may push the devices to the limits in terms of accuracy or operation speed that is fundamentally possible."

The authors of this review consider factors in the discipline including the extent to which a quantum system can be established, controlled and observed without causing this superposition to collapse, something which seriously impedes the stability of quantum computers.

The review also suggests that just as conventional engineers have a control theoretical framework to rely on, the training of future "quantum engineers" may require a similar framework which is yet to be developed.

A quantum system that unifies theory and experiment is one of the current research goals of the field with the authors pointing out that this will also form the basis for the development of optimal control strategies.

As well as assessing the recent progress towards this goal, the team lay out some of the roadblocks that may lie ahead for the field. Roadblocks that will need to be overcome if a quantum technological future is to be manifested. ■

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Embarking on the Second Quantum Revolution

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The initial foundations of Quantum Physics date back more than hundred years. Quantum Mechanics allows to understand and to calculate the properties and the behaviour of microscopic physical systems and was a big step forward. The First Quantum Revolution with the application of this knowledge invoked ground-breaking technological advancements like transistors and lasers. Meanwhile, science research created the ability to identify, control and manipulate individual quantum objects like photons, electrons, atoms and molecules. These abilities are the basis for new, quantum-driven, technologies. Presently the Second Quantum Revolution is evolving with an incredible speed, leading to disruptive novel technologies. They have the potential to revolutionize the way how we do science in future and to invoke a strong impact on our economy as well as on our society. Various rating agencies predict for Quantum Computing business volumes of $450 billion within the next 15 years and estimated $5 - $10 billion within the next three to five years for users. The competition in this novel Quantum Technology field is very strong.

Paying tribute to the crucial importance of this new technology the First EPS Forum 2022, which took place beginning of June at the Sorbonne University in Paris, featured several highlights in Quantum Technology. The community, including many young scientists as well as recognized seniors, were joined in listening to presentations for example by Nobel Prize Laureate Prof. Serge Haroche on the "Power and Strangeness of Quantum Physics", and on Photonic Quantum Technology. They were debating in a panel on the vision for Quantum Computing as well as exploring it in real hand-on exercises. Actions like this are highly welcome and preparing the community to familiarize and become "Quantum-Ready" for the future.

Quantum Technologies employ physical properties that are very different from classical concepts. Here Superposition, Entanglement and Uncertainty, with its randomization, play a crucial role. Quantum Technologies comprise a large variety of aspects. One very prominent area is given by Quantum Computer Hardware and their Quantum Computing Applications solving complex problems that cannot be addressed with conventional computing or speeding up Big Data analyses to master the challenges ahead of us. Creating and developing Quantum Materials with astounding novel properties, could be the basis for inventing future electronic devices performing faster but with less energy consumption. And then of course Quantum Sensing, opening with unprecedented precision novel opportunities for complex monitoring and experiments beyond our present imagination. Also, Quantum Communication is an area of intense interest due to its prospect of very secure information transmission providing a novel realm for cyber security for financial and other transactions or a faster Quantum Internet.

The novel Quantum Technologies open various windows to potential discoveries in science or solutions for society for example in fighting diseases. At the same time, they imply a strong influence on economy with the eventual industrial application. In order to benefit best and to enable profiting at the first possible instance, Europe is acting via the European Research Council and the European Innovation Council, and has invoked several funding lines to support research and commercialization, for example via the Quantum Flagship or pathfinder challenges to identify alternative approaches in Quantum Technology.

This fourth issue of the Europhysics News features Quantum Technologies with three dedicated articles: "Highly Unidirectional Molecular Motors" by Oliver Gröning, "Cold Rydberg Atoms" by Thierry Lahaye and "Quantum Games" by Sabrina Maniscalco. They open the possibility to look into three different topics in more detail.

Quantum Technology is part of our future. We, physicists in the EPS, are well positioned to become Quantum-Ready and inspire the public. ■

Kerstin Borras,
Deutsches Elektronen-Synchrotron – DESY
RWTH Aachen University, Germany

A Quantum Ecosystem like no other

A barrierless, connected community is at the heart of the national quantum initiative in the Netherlands. In 2021, Quantum Delta NL was awarded €615 million from the Dutch government to implement the National Agenda for Quantum Technology (NAQT). At the core of this agenda is building a unique quantum ecosystem around the five hubs of quantum research excellence: Delft, Eindhoven, Leiden, Twente and Amsterdam (DELTA).

▲ Architect's vision of what the House of Quantum could look like (by Cepezed).

The spark that triggers the growth of almost every high-tech ecosystem around the world comes from the knowledge centers. They are where the cutting-edge research is being pursued and where the brightest talents are being developed who will ultimately push the laboratory research out into the real world. The quantum ecosystem in the Netherlands is no different.

The Delft University of Technology (TU Delft) and its research center QuTech have seen seven quantum spin-out companies form over recent years, all with a hardware focus: Single Quantum, Delft Circuits, QBlox, Orange Quantum Systems, QuantWare and QphoX. Elsewhere in the QDNL ecosystem there are several more established companies, with even more being developed: Quix Quantum (Twente); Leiden Cryogenics and Onnes Technologies (Leiden), Appsilon Enterprise (Delft) and Qu & Co, which recently merged with France-based Pasqal (Amsterdam). The influx of funding for research and capital investment in the companies creates a lot of new work opportunities. To help facilitate top talent joining this rapidly growing quantum ecosystem, every job and internship in both academia and industry are collated on the Netherlands' national job board (jobs.quantumdelta.nl).

This high concentration of quantum companies in Delft and the Netherlands has created a unique opportunity to build a world leading quantum community. The physical embodiment of that is the national quantum campus – a collection of buildings in all the hubs that are integrated and connected across the ecosystem. The Quantum Delta NL agenda originally planned for 7 buildings, totaling >45,000m^2 of technical labs, clean rooms, and offices. The first of those buildings will be open from the fall of 2022 in the Delftechpark, next to the TU Delft campus. It houses four companies, a community lab (rentable millikelvin fridge), and community space (restaurant, event space, flex working areas and meeting rooms). This will serve as the epicenter of the community in Delft, until the opening of the House of Quantum headquarters on the TU Delft campus in 2025. Memberships to this community building are available to international parties to allow them to sample the Dutch quantum community during working visits and discuss setting up potential satellite operations.

If you are interested in connecting with the QDNL ecosystem in any way, reach out via info@quantumdelta.nl and sign up to our monthly newsletter via our website. ■

▼ Photo from the QDNL "Nodes of One Network" event in Amsterdam 2021.

QUANTUM GAMES – A WAY TO SHED LIGHT ON QUANTUM MECHANICS

Caterina Foti[1,2], Elsi-Mari Borrelli[1], Daniel Cavalcanti[1], Rosario Maniscalco[1], Boris Sokolov[1,3] and Sabrina Maniscalco[1,2,3] – DOI: https://doi.org/10.1051/epn/2022403

[1] Algorithmiq Ltd, Kanavakatu 3 C, FI-00160 Helsinki, Finland
[2] InstituteQ – The Finnish Quantum Institute, Department of Applied Physics, School of Science, Aalto University, FI-00076 Aalto, Finland
[3] InstituteQ – The Finnish Quantum Institute, Department of Physics, University of Helsinki, FI-00014 Helsinki, Finland

Today the term 'quantum' is often encountered in the media, not only in connection with scientific research and technology, but also in combination with almost anything that may come to mind. You can find quantum chocolate, the quantum car, soap, love, the mind, the soul, etc. This reflects, on one hand, how the notion of quantum physics is somehow associated to efficiency and technological power, but also how the counter-intuitive behaviour of quantum mechanics remains elusive to most people. As we are entering an era of quantum technologies, it is essential to shed some light on the basic principles of quantum physics. Games can provide a versatile and fun way to immerse people from all backgrounds to the counterintuitive rules of the quantum world.

▲ Q|Cards> Online is a game introducing and teaching the basics of quantum computing, without requiring previous experience in quantum physics.

First of all, why popularise quantum physics?

Today, when people speak or write of quantum technologies, they mean a broad range of devices that function, in their essence, by exploiting quantum effects. These new quantum technologies are related to the recent ability to control and observe matter at the level of individual quantum particles. It has been discovered, for instance, that entanglement enables completely new ways of manipulating and transmitting information, and that superposition of quantum states and interference can bring a great advantage in certain algorithms.

Among quantum technologies (QT), the holy grail is certainly the quantum computer, which promises to solve problems that are intractable today. Quantum computers are expected to profoundly affect life sciences, robotics, artificial intelligence, data storage and security, and potentially every field that relies on computing power. It is believed that they will help us solve many of the great challenges of our century, from healthcare to energy and the environment.

Until recently, QT were the preserve of a small number of scientists. However, the skills required to address the big challenges are diverse, and concern not only quantum physicists, but also professions such as engineers, computer scientists, mathematicians, business and marketing experts. Taking into account the stakeholders of potential QT applications, we should add to the list also chemists, biologists, natural and material scientists, medical doctors, economists, brokers, analysts, traders. It is clear that the development of multifaceted quantum literacy, capable of adapting to different languages, is crucial to the emergence of the quantum ecosystem.

In this context, education and training is *a priori*ty, and specific curricula to address this transformation are being designed all over the world. At the same time, in order to build a society capable of making responsible decisions, it is important that a broader cohort than just school and university students is informed about quantum science and technology.

QPlayLearn: quantum physics for everyone, with games

To address the challenges and opportunities of a widespread quantum literacy, the collaborative online platform QPlaylearn (https://qplaylearn.com) was conceived and implemented, with the aim of teaching quantum science and informing about the impact of QT to everyone, regardless of their age or background.

The QPlayLearn (QPL) online platform offers tailored contents for different target groups, focusing on the following: i) Teachers, students and curious learners; ii) Corporate executives, employees, policy makers and journalists; iii) Artists, curators and cultural managers.

Despite diversification following the different needs of each audience, the core of our approach is that different types of intelligence dominate the learning process of each individual. In this regard, QPL develops and curates various multimedia contents to build intuition and engagement through games and videos, grasp physical concepts through easy-to-follow explanations, acquire the formal understanding through the mathematics. An essential ingredient in QPL's approach is playfulness. Fun and interactivity increase the effectiveness of the learning process and make concepts less intimidating. In this, games can play a relevant role.

The application of game elements and digital game design techniques to non-game problems has gained much attention in recent years and applications have been successfully implemented in various contexts, from real, • • •

more 'serious' games related to business and social impact challenges, to games exploited as an educational strategy.

Cognitive neuroscience has provided considerable empirical evidence on how our brains are positively affected by games from a learning perspective. Games are an effective way to learn because, increasing attention and focus levels, keeping our brains engaged and happy, they create favourable biochemical conditions for synaptic networks to be created and learning to happen. In fact, not only game-based learning (GBL) can help especially children to develop a set of skills that are considered to be essential in their future jobs: critical thinking, problem solving, resilience, collaboration, analytical skills, but as they allow gamers-learners to enjoy challenges and play, which increases the willingness and excitement to take risks and even accept failing as part of improvement and learning processes, whereas risk-taking is otherwise a step people typically tend to avoid. More in general, GBL allows people of all ages to approach learning with a hands-on, inquiry-driven, game-based sets of activities which hard-wire knowledge, skills and competences in our brains.

Indeed, given the pressing need to make QT accessible to a wider audience and to facilitate the inclusion of stakeholders in the debate on the topic, learning quantum concepts through games has gained prominence as an approach to support the quantum community at large in its outreach and education efforts [1]. Quantum phenomena and problems require imagination, thinking outside the box and exploring broad solution landscapes. GBL could therefore be a valuable resource for both real games and learning.

Among the resources offered by QPL, QUEST consists of a quantum dictionary containing a list of key quantum concepts. Each entry is explored using a methodology based on the different approaches to learning described above, from intuition to formalisation. In particular, all the various QUEST entries include a 'Play' section in which proprietary games, developed by the QPL team, are combined with games developed by other stakeholders and collaborators as part of the QPL network, carefully selected from the available games. Some of the games were born in the context of the Quantum Game Jams we co-organised, as in the case of the board game Q|Cards> developed during the Quantum Game Jam 2019 by some of the authors and other collaborators, or the more recent Potatoes Quest, developed during the IF Quantum Game Jam 2020 by two students at the University of Pisa.

In QPL, all games are used with the aim of helping learners develop insight into the 'strange' (to the human eye) behaviours of QP. Therefore, games are used as educational tools, hence all falling under the umbrella of the GBL. Currently, concepts explored through the games published on the QPL platform are: quantum physics, quantum state, qubit, superposition, entanglement, quantum measurement, wave-like behaviour, tunneling, quantum technologies. In the following section, we will present one of these games.

▾ In the tutorial of Q|Cards> Online qubits are represented as merpersons sitting on a ball. In the 'Cards Library' the players/ learners can find a description of the action performed by each card/gate and play with the input state to see how the output changes.

Q|Cards> Online: a new video game to learn about quantum computation

Q|Cards> started as a prototype board game developed during the Helsinki-based Quantum Game Jam 2019 'Quantum Wheel', later refined and co-produced together with the Finnish company MiTale. In Summer 2021, QPL launched the mobile game Q|Cards> Online, a fully digital and online multiplayer version of its tabletop ancestor Q|Cards> [2].

As in the board game Q|Cards>, each player starts with a qubit in the |0> state and the goal during the game is to maximise the probability that, at the end of each turn, their qubit goes from |0> to |1>. During their turn, players can apply their cards to any player's qubit line, which corresponds to applying single- or two-qubit gates and forming a quantum circuit together with the cards/gates placed by the other players.

There are multilevel ways to play the game, just for fun or for delving into the physics behind it. Either way, to win or at least play consciously, players need to understand even roughly what a qubit is, how to manipulate it through gates and also why probabilities are involved. Therefore, Q|Cards> can be exploited as an educational resource to teach the basic notions of quantum information and computing, but also QP concepts such as superposition, entanglement, and quantum measurement.

In addition, the game runs on a real quantum device. The 2- to 5-qubit quantum circuit resulting from the game is automatically translated into IBM Qiskit and the corresponding circuit is simulated or executed on a real IBM Q cloud quantum computer.

Q|Cards> Online is accompanied by a tutorial explaining rules and actions of the various cards/gates, where qubits are pictorially represented as merpersons sitting on a ball. The imaginative pictures allow for a level of explanation that can be adapted to the audience. Hence, it is sufficient for pupils and young learners to think about the upright and upside down configuration of the seated merperson representing the qubits' basis states |1> and |0>; for high-school students it is easy to explain the Bloch sphere, which of course lies behind the representation of the merpersons; for a more mathematically advanced audience, density matrices can also be introduced, since in the tutorial mixed substates are also visualised as merpersons falling into their own ball, while the entangled Bell states are visualised as merpersons connected by branches still sitting on the surface of their own ball.

The idea of educational and popularisation resources offering the possibility of multilevel education is the mission behind each and every content and project developed by QPlayLearn. Regardless of the expertise of the target audience, there is always a solid scientific background behind images and examples used to popularise QP and QT. Multilevel educational resources can help avoiding misleading analogies and oversimplified explanations, a risk in quantum popularisation especially in contexts where the proper mathematical formalism cannot be used. ■

About the Authors

SM is Professor of Quantum Information, Computing and Logic at the University of Helsinki, vice-director of InstituteQ, the Finnish quantum institute, CEO and co-founder of Algorithmiq, a startup developing quantum algorithms for life sciences. EB, DC, CF, BS have PhDs in quantum physics and are all part of the Algorithmiq staff. RM holds a PhD in Educational Sciences and has worked in policy making in the EU and OECD. All authors are members of the QPlayLearn team and are passionate about innovative educational and outreach projects, particularly related to quantum science and technology.

Acknowledgments

The authors thank the entire QPL team, in particular Dr. Guillermo García-Pérez, who developed the game concept and design, and Dr. Matteo Rossi, who developed the game design and code.

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THE WAR IN UKRAINE: DOES PHYSICS HAVE A FUTURE?

Yurij Holovatch[1], Alexander Kordyuk[2] and Ihor Mryglod[3] – DOI: https://doi.org/10.1051/epn/2022404

[1] Institute for Condensed Matter Physics of the National Acad. Sci. of Ukraine, Lviv, Ukraine & L4 Collaboration and International Doctoral College "Statistical Physics of Complex Systems", Leipzig-Lorraine-Lviv-Coventry, Europe
[2] Kyiv Academic University & G.V. Kurdjumov Institute of Metal Physics of the National Acad. Sci. of Ukraine, Kyiv, Ukraine
[3] Institute for Condensed Matter Physics of the National Acad. Sci. of Ukraine, Lviv, Ukraine

The war in Ukraine is still going on. The number of victims is increasing every day. Many research centers are destroyed, researchers are displaced, and the conditions and nature of work in almost all regions of Ukraine have undergone significant changes. Is it time to talk about the future of physics in Ukraine under such conditions now? It is our deep conviction that it is necessary.

◂ P. 20: Ukrainian physicists at IFW Dresden in April 2022. © IFW Dresden.

For most Kyiv families, the foreseen war started unexpectedly on 24th of February at 4 am by explosions and alarming telephone calls from friends. In a few hours the roads were blocked by millions of cars, some were trying to reach the workplaces but most were aimed to the west. Surprisingly, the internet and all other telecommunications remained working and all the civilians, either in traffic jams or discovering not well prepared shelters, were united in following the news and believing in military forces. The scientists behaved similarly. All research was stopped for about a month and researchers in shelters, jams or trenches got much time to think about the future of Ukrainian science.

The Institute for Condensed Matter Physics of the National Academy of Sciences of Ukraine (ICMP NASU) in Lviv holds its regular seminars on Thursdays. The online seminar scheduled for the 24th of February appeared to be an extraordinary one: instead of physics we discussed what is going on in our country and how to stand and cope with the new wave of Russian aggression. Our daily work of physicists seemed meaningless in the face of existential threat to us and to the whole world. The same day we started to receive messages of support from our colleagues from all over the world [1,2].

Kharkiv, the main scientific, cultural and industrial center at the East of Ukraine was - and continues to be - severely damaged by Russian attacks. Already at the first days of the war the missiles hit the fluorescence spectroscopy laboratory of the Department of Medical Physics and Biomedical Nanotechnologies, ruined other buildings of the physical and technical department of Kharkiv National University, and destroyed the neutron source substation of the Kharkiv Institute of Physics and Technology NASU [3,4]. All seven buildings of the Usikov Radiophysics and Electronics Institute NASU were significantly damaged by rocket and bomb attacks, and most of the experimental installations of the institute were fully destroyed.

Besides these cities, physical research and education has a long-standing tradition in all regions of Ukraine. At the beginning of Ukrainian independence in the 1990s, physics and related sciences were the dominant fields of research. To a large extent, this had its roots back in the USSR, which, at the request of the military complex, had an orientation on solid-state physics and, like almost all sciences in the former USSR, was largely closed off from the world. The main institutes of the physical profile were focused on defense problems and were financed to a large extent from the corresponding funds. As examples may serve the Paton Electric Welding Institute NASU, which made a significant contribution to the technology of production of tanks and other heavy weapons, or the aforementioned Usikov Institute of Radiophysics and Electronics and its developments of cruise missile control systems, tactical air defense equipment, *etc.* In the next thirty years, scientific relations with the world expanded significantly, internships of Ukrainian scientists in leading international centers of physics became a practice, and the field of fundamental research expanded. To a large extent, this process was facilitated by the Science and Technology Center in Ukraine [5], which opened up new perspectives for international cooperation, as well as Ukraine's accession to the EU framework cooperation programs. New principles and approaches began to be used in the organization of research in Ukraine, in particular due to the creation of the National Council of Ukraine for Science and Technology Development and the start of the National Research Foundation of Ukraine [6]. Representatives of Ukraine participated in a number of scientific collaborations, including at the Large Hadron Collider.

The war affected all aspects of life in Ukraine and all its residents. The scientific community, in particular the physical one, was no exception. In this respect, among the main problems one has to mention the following:

- **Scientific infrastructure.** Research centers in the occupied zone have stopped their activities. The war is a destruction that also affects the premises of scientific institutions, the equipment and entire infrastructure are destroyed. As a result of the shelling of Kyiv, Dnipro, Kryvyi Rih and Kharkiv, the occupation of Mariupol and Kherson, as well as the seizure of nuclear energy facilities (Chornobyl, Zaporizhia) and the bombing of large chemical production enterprises, there were growing risks for both the environment and people. Restoration of the scientific infrastructure will require significant financial investments.
- **Scientific personnel.** During the war, a large number of forcibly displaced persons left their places of permanent residence due to the threat to their lives and the lives of their families. Many scientists from Ukraine worked in leading centers of the world even before the war. This trend, which began after the collapse of the USSR and continued for decades, has now significantly intensified. Some scientists are fighting in the ranks of the Armed Forces of Ukraine, there are many casualties among the civilian population, including the science community. Due to the threat of missile strikes, the conditions and nature of work in almost all regions of Ukraine have undergone significant changes.
- **Topics and requests for research.** In the conditions of war, military expenditures become an absolute priority, and therefore other budgetary expenditures, in particular for science, are reduced. The priority areas of research are those that can contribute to victory and are focused on quick applied results. Basic research is in a dangerous state. It is obvious that all these problems will be acutely felt in the post-war period as well. The dynamics of the development of all sciences in Ukraine, particularly physics, will depend on their solution.

▲ A neutron source substation at Kharkiv Institute of Physics and Technology destroyed by Russian attacks on 6 March, 2022. © State Nuclear Regulatory Inspectorate of Ukraine.

The war in Ukraine is going on. The number of its victims is increasing every day. A significant number of scientists are called to the ranks of the Armed Forces or are involved in territorial defense units. Thousands of them work as volunteers and do their best to help financially, facilitate the placement of temporarily displaced persons, or help the military in other ways. Note that due to the peculiarities of wartime, women, the elderly and children dominate among temporary refugees to other countries of the world, while men under sixty remain in Ukraine and form a mobilization reserve. Considerable attention is paid in Ukraine to the preservation of the infrastructure of scientific institutions, primarily in terms of the implementation of urgent works to save damaged buildings and their temporary conservation until the end of hostilities. In most physical laboratories, research work continues, although for obvious reasons, in volumes smaller than before the war. The first attempts to analyze the impact of the war on scientific research in Ukraine have already appeared [7]. Is it possible to talk about the future of physics in Ukraine under such conditions? In our deep conviction, it is not only possible, but also necessary.

In the long term, Ukrainian science evidently would require a "Marshall Plan" to survive. We may hope to get easier access to European research infrastructures and the international grants like within Horizon Europe, but development of joint research labs and institutes in Ukraine would be especially helpful. One of the key tasks will be not just to restore the pre-war level of scientific infrastructure, but to create new points of rapid growth - possibly through the creation of a few centers of interdisciplinary basic research with modern equipment as well as with the access to global computer facilities and the wide involvement of international specialists in research topics. These centers should be closely integrated into the educational process. It could give a powerful stimulus both for the training of young physicists and for maintaining the level of basic research with the integration into the European Research Area.

Some forms of help to Ukrainian scientists and students emerged immediately with the rise of the war. We have got a number of offers from colleagues around the world to host Ukrainian scientists. Examples are PAUSE and JESH programs in France and Austria and many others [8]. In places with long lasting collaborations the special programs have been started. For example, the Ukraine Scientific Scholarship Program has been promptly established in Dresden, and in the first month 19 students and scientists, mostly physicists, have gone to the Leibniz Institute for Solid State and Materials Research Dresden to continue their research [9]. Such scholarships remain attractive also in the middle term, when it is about establishing new collaborations. Although there is a danger of a new wave of "brain drain". Other positive examples of foreign help to Ukrainian researchers or students staying in Ukraine are the IRIS-HEP Ukrainians Fellows program or the Pauli Ukraine Project [10]. The remote projects seem to be indispensable to support Ukraine and its researchers and lecturers in the middle time scale.

In the current situation, it also increases the importance of PhD studies carried out in frames of the split-side agreements (co-tutelle). To give an example, the first co-tutelle PhD thesis in the field of physics was defended in 2008 within collaboration between the University of Lorraine (then – Henri Poincaré University Nancy) in France and ICMP in Lviv. Now this collaboration is widened to the International Doctoral College "Statistical Physics of Complex Systems" that joins ICMP with Universities of Lorraine, Leipzig and Coventry. We think that such and similar initiatives have to be further supported both by the local decisions of University councils as well as on the level of international programs.

As sociological studies show, the vast majority of Ukrainians are convinced of the victory of Ukraine, despite the terrible methods of waging war (methods that have been recognized globally as terrorist in essence), when the Russians try to intimidate and in this way subjugate through the total destruction of civilian infrastructure objects and bombing of peaceful residents. But the victory (as Ukraine imagines victory) is possible only when the international community helps Ukraine to endure. This is the way to lasting peace in Europe and the world, this is the way for peace in Ukraine and this is the way when physics (like other sciences) will have a future in Ukraine. And every citizen of the world can contribute to this process, or be a passive observer, and therefore an active opponent of such a scenario. This is an answer without guile to the question about the future of physics in Ukraine. ■

About the Authors

Yurij Holovatch is a chief researcher at the Institute for Condensed Matter Physics of the National Academy of Sciences of Ukraine and a full member of the Academy. PhD (1984) and DSc (1991) in theoretical physics. He is a co-founder and a co-director of the L4 Collaboration and International Doctoral College "Statistical Physics of Complex Systems". His principal research fields are phase transitions and critical phenomena, complex systems, digital humanities, and the history of science.

Alexander Kordyuk is experimental physicist with main expertise in the fields of superconductivity and electron spectroscopy, PhD in solid state physics (1993), DSc in superconductivity (2000), professor in applied physics and nanomaterials (2020), and full member of the National Academy of Sciences of Ukraine in experimental physics of quantum materials (2021). Now he serves as director of Kyiv Academic University and head of Department of Superconductivity at the Institute of Metal Physics of NASU.

Ihor Mryglod is a chief researcher at the Institute for Condensed Matter Physics of the National Academy of Sciences of Ukraine. He obtained his PhD in 1988 and defended his doctoral thesis in 2000. In 2012 he was elected as a full member of the NASU in physics of liquid state. Between 2006 and 2021 he worked as director of the ICMP NASU. His main research interest relates to phase transition phenomena, non-equilibrium statistical theory, and fluid dynamics.

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WHEN A MOLECULAR MOTOR DOES THE QUANTUM LEAP

[1,2]Oliver Gröning[1], Samuel Stolz[1,2], Jan Prinz[1,2], Harrald Brune[2], Roland Widmer[1]

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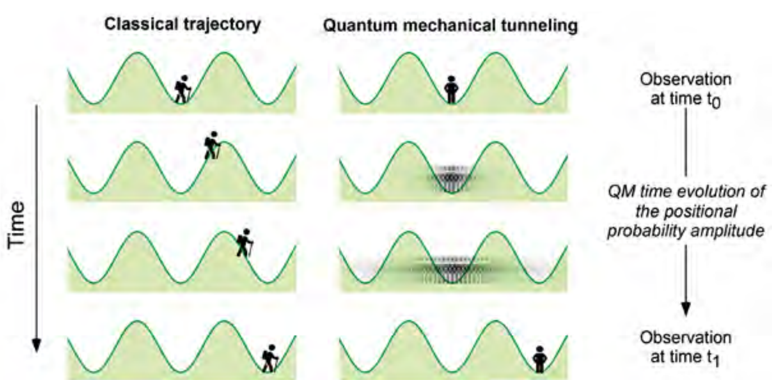
[1] Empa, Swiss Federal Laboratories for Materials Science and Technology, 8600 Dübendorf (Switzerland)
[2] Institute of Physics, École Polytechnique Fédérale de Lausanne, 1015 Lausanne (Switzerland)

In his seminal 1959 lecture "There's Plenty of Room at the Bottom" Richard Feynman has put forward two challenges [1] .The first was to shrink letters to a size, which allowed writing the whole Encyclopedia Britannica on the head of a pin - which was achieved in 1985 [2].The second challenge read: "It is my intention to offer a prize of $1,000 to the first guy who makes a rotating electric motor which can be controlled from the outside and, not counting the lead-in wires, is only 1/64th inch cubed" [1].

Less than a year later, William McLellan met this challenge by scaling down an electric motor consisting of just 13 parts and weighing some 250 μg to the required size [3].

Motivated by the ubiquity of nanoscale machines in biology, the desire to achieve ever smaller sizes remained vivid and the first motors brought to molecular dimensions were reported in 1999 [4,5]. To this day, most synthetic molecular machines, although driven by quantum processes such as light absorption and bond reconfiguration [6], exhibit classical kinetics. This contrasts with quantum mechanical real space tunneling. As illustrated in Fig. 1, instead of a quasi-continuous classical trajectory, the process of a particle overcoming a potential barrier by tunneling looks more like an abrupt leap. In a quantum system, having determined a particle's position at time t_0 by measurement, its wave function will subsequently spread out over time, such that it acquires a nonzero probability to be in places, where it would be classically forbidden. When the position of the particle is measured at a later time t1 and its wave function collapses with non-zero probability in the adjacent well, it might thus seem to have "tunneled" through the potential barrier.



▼ **FIG. 1:** Illustrative comparison of a classical (left) and a quantum tunneling (right) transition from one minimum of a potential energy landscape to another.

For quantum mechanical tunneling to occur with non-vanishing rates the requirements are that the energy barrier between the initial and final configuration is small, the tunneling distance short, the mass of the system in motion light, and the operation temperature low. To give an idea of the scales: on a copper surface a hydrogen atom with mass m_H = 1.67e-27 kg tunnels a distance of 2.55 Å (= 2.55e-10 m) across a potential barrier of about 0.2 eV (= 3.2e-20 J) with an average rate of about once every 40 minutes [9]. Scaling down a unidirectional molecular motor to meet the requirements for real space tunneling is therefore a formidable challenge.

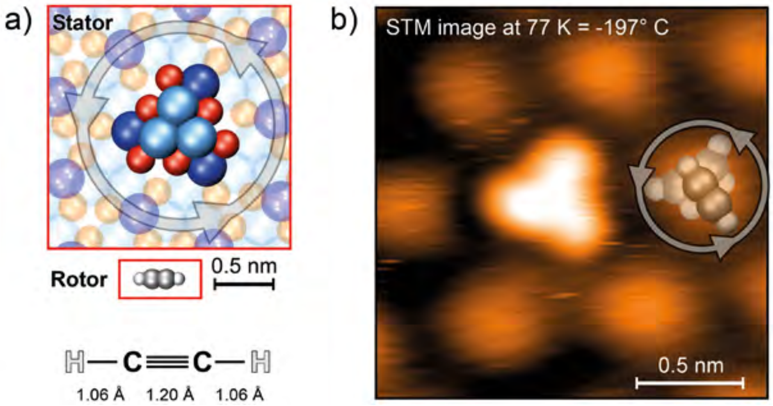
Like an ordinary electric motor, our atomic motor consists of a stator and a rotor. As we want to achieve a directional motion, either the stator or the rotor should show a handedness or chirality, which makes a clockwise (CW) rotation inequivalent to a counter-clockwise (CCW) turn. An atomic cluster of the surface of a chiral Palladium-Gallium (PdGa) crystal realizes our chiral stator [7,8]. Figure 2a shows its pinwheel-like atomic structure, which consists of 3 central Palladium atoms (light blue), which are surrounded by deeper layers of 6 allium (red) and 3 Palladium atoms (dark blue). Having a chiral stator allows us to use very small and symmetric rotors such as a single rod-shaped acetylene (C_2H_2) molecule with a length of about 3.3 Å and a mass of 26 Dalton (= 4.32e-26 kg). The motor self-assembles by exposing the PdGa surface to acetylene gas (at 10e-9 mbar) at low temperatures (below 170 K). Figure 2b shows the scanning tunneling microscopy (STM) image of such a motor at 77 K. The three-lobed bright feature in the center shows a rotating acetylene molecule, where the rotation is much faster than the frame rate of the STM (about one frame per minute). This means the image represents a time average of the molecule in all its meta-stable rotation states as schematically shown on the right hand side of Fig. 2b).

Only by reducing the temperature to 5 K, the rotation becomes slow enough for the STM to image the molecule in each of its 3 distinguishable rotational states (see. Fig. 3a and 3b). One can see that from one frame to the other that the acetylene molecule rotates by 60° in the CCW direction with a bit of eccentricity.

As the frame rate of STM is rather slow, we use a different mode of observation, which drastically increases the time resolution. As shown schematically in Fig. 3c, instead of constantly imaging the acetylene molecule, we 'park' the tip of the STM at a certain position over the molecule. In the 'parking' mode, each rotation of the molecule changes the current between the tip and the sample. Figure 3d shows such a current-time diagram with the tip parked in the position denoted by the marker in rightmost image of Fig. 3a. This time series is characterized by 3 distinct current levels (A, B and C), each corresponding to one rotational state of the rotor, and sudden transitions, *i.e.* jumps, between them. Based on the distance between the molecule and the tip, we can correlate the current levels with the rotational states observed in the STM topographies (see Fig. 3a). What is remarkable is that the sequence of rotational transitions from A to B to C and back to A, which corresponds to a 180° rotation, is maintained throughout the whole sequence of the 23 rotation-events, which implies unidirectional CCW motion of the rotor. Under the best conditions, the probability of a jump in the wrong direction is about 1%.

As mentioned before, the rotation rate or rotation frequency is temperature dependent and Fig. 4a shows this dependency in more detail. From about 15 K onwards, we see that there is an exponential increase of the rotation frequency, from which we can deduce an energy barrier height between the rotation states of about 25 meV. We estimate that at 77 K (see Fig. 2b) the rotor spins faster than 100'000 times a second. All temperature induced rotations are, however, not directional. This is in accordance with the 2^{nd} law of thermodynamics. As we control temperature macroscopically, the stator, the rotor and the STM tip are in thermal equilibrium and a thermally activated, directional motion is impossible because it would decrease entropy.

The rotation of the rotor, however, is not just activated by temperature; the tunneling current of the STM •••



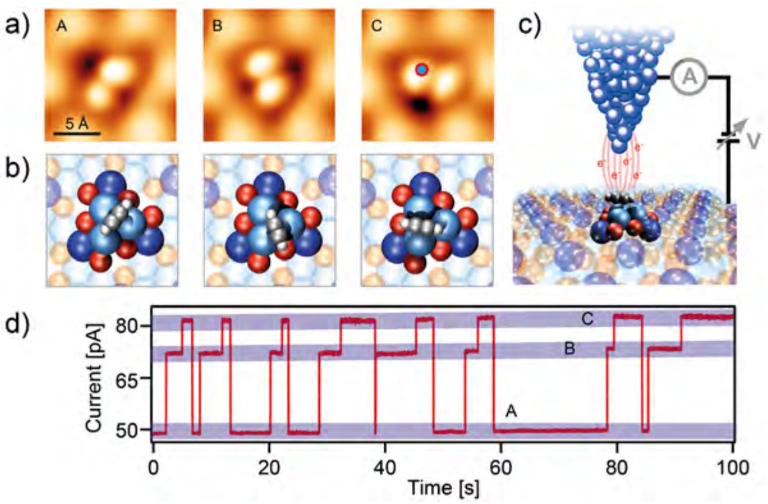
▲ **FIG. 2:** a) Schematic representation of the atomic structure of the stator (blue balls represent Pd and red ones Ga atoms) and the rotor of the motor. b) STM image of a fast-rotating C_2H_2 molecule at 77 K, with the schematic representation of the time-averaged configuration of the rotor as inset.

can induce rotation events too. Figure 4b shows the rotation rate as a function of the bias voltage between tip and sample at a constant current of 100 pA. As for the temperature dependence, we observe a sharp increase of the rotation frequency above a threshold of about 35 mV independent of polarity. In contrast to the non-directed rotation induced by temperature, the rotations induced by the STM current are directional for voltages slightly above the threshold. With increasing voltage, the direction of the rotations become progressively random. The fact that there is linear relationship between the STM current and the rotation frequency implies that a single electron transfers some of its energy to the rotor, which enables it to overcome the potential barrier between two rotation states. This is a very rare event and only about 1 out 1 billion electrons flowing through the motor actually triggers a rotation. Directionality is enabled due to friction as the rotor requires a little bit less activation energy to overcome the barrier in the CCW direction. The reason is that the trajectory in the CW direction is a bit shorter (a result of the stator being chiral) and the rotor loses less energy on this path as compared to the CW one, thus resulting in a directional rotation at low activation energies.

So far, we have been discussing the classical motion of the motor and we can understand it in terms of Arrhenius' law when it is temperature activated or Newton's mechanics with friction when it is electrically stimulated. However, if we turn our attention back to Figures 4a and 4b, we see that below the threshold temperature and voltage (*i.e.* in the non-shaded regions of the diagrams), the rotation frequency does not decrease, but remains constant. This is the signature of the quantum-tunneling regime, which is at first glance astonishing because the acetylene rotor is massive, 26 times heavier than the hydrogen atom tunneling on a copper surface. However, for the rotation it is not the mass, which is relevant but the moment of inertia, which is about 5.6e-46 kgm^2. Furthermore, with 25 meV the potential barrier is small and we expect a higher tunneling rate than for H on copper. Lastly, there is also an experimental test if this can be quantum tunneling. By replacing the hydrogen atoms in the acetylene by deuterium, we increase the moment of inertia by only 20%, but the tunneling rate however, drops by a factor of 4. This extreme sensitivity agrees with the theoretical expectations for quantum tunneling [7,9].

Open questions, however, remain. The rotation in the tunneling regime is directional too, which is surprising, because an asymmetrically skewed rotation potential alone does not yield asymmetric tunneling rates. From fundamental thermodynamic considerations, the directional tunneling motion must be related to dissipative processes. Further investigation, *e.g.* by ultra-fast STM, are needed to elucidate the relationships between atomic friction and directional tunneling. ■

▼ **FIG. 3:** a) STM images and b) the corresponding atomistic models of one acetylene molecule on the Pd_3:A surface in its three distinct, energetically equivalent, 60° rotated states. c) Schematic illustration of the experimental setup to probe and drive the acetylene on Pd_3:A molecular motor with an exemplary experimental current-time sequence in d). A time-lapse movie of the rotation can be found here: https://www.youtube.com/watch?v=g7COlp6hK3A.



About the Authors

Oliver Gröning as head and **Roland Widmer** as his deputy of the functional surfaces research group at Empa are engaged with research on intermetallic compounds. **Harald Brune** is full professor at the EPFL, where his research is concerned on novel physical and chemical properties of nanostructures at single crystal surfaces. After their PhDs at Empa, **Jan Prinz** is now head of the failure analysis lab team at u-blox in

Switzerland and **Samuel Stolz** pursues postdoctoral research on Transition Metal Dichalcogenides at the UC Berkeley.

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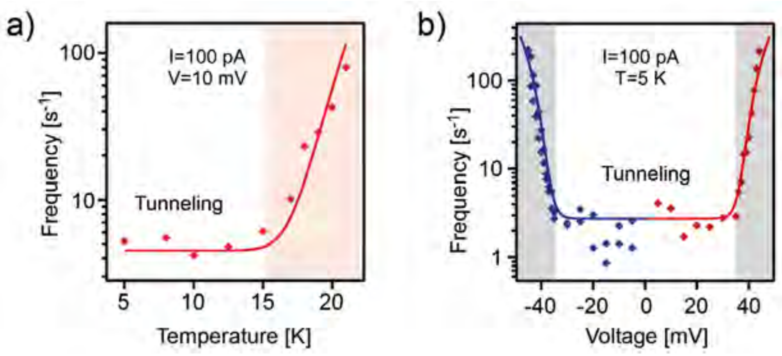

▲ **FIG. 4:** The dependence of our molecular motor's rotation frequency and directionality on a) temperature and b) applied bias voltage. The red and grey shaded regions in a) and b) denote the thermally and electrically activated rotation respectively; in the non-shaded regions, the non-zero constant rotation frequency shows tunneling characteristics.

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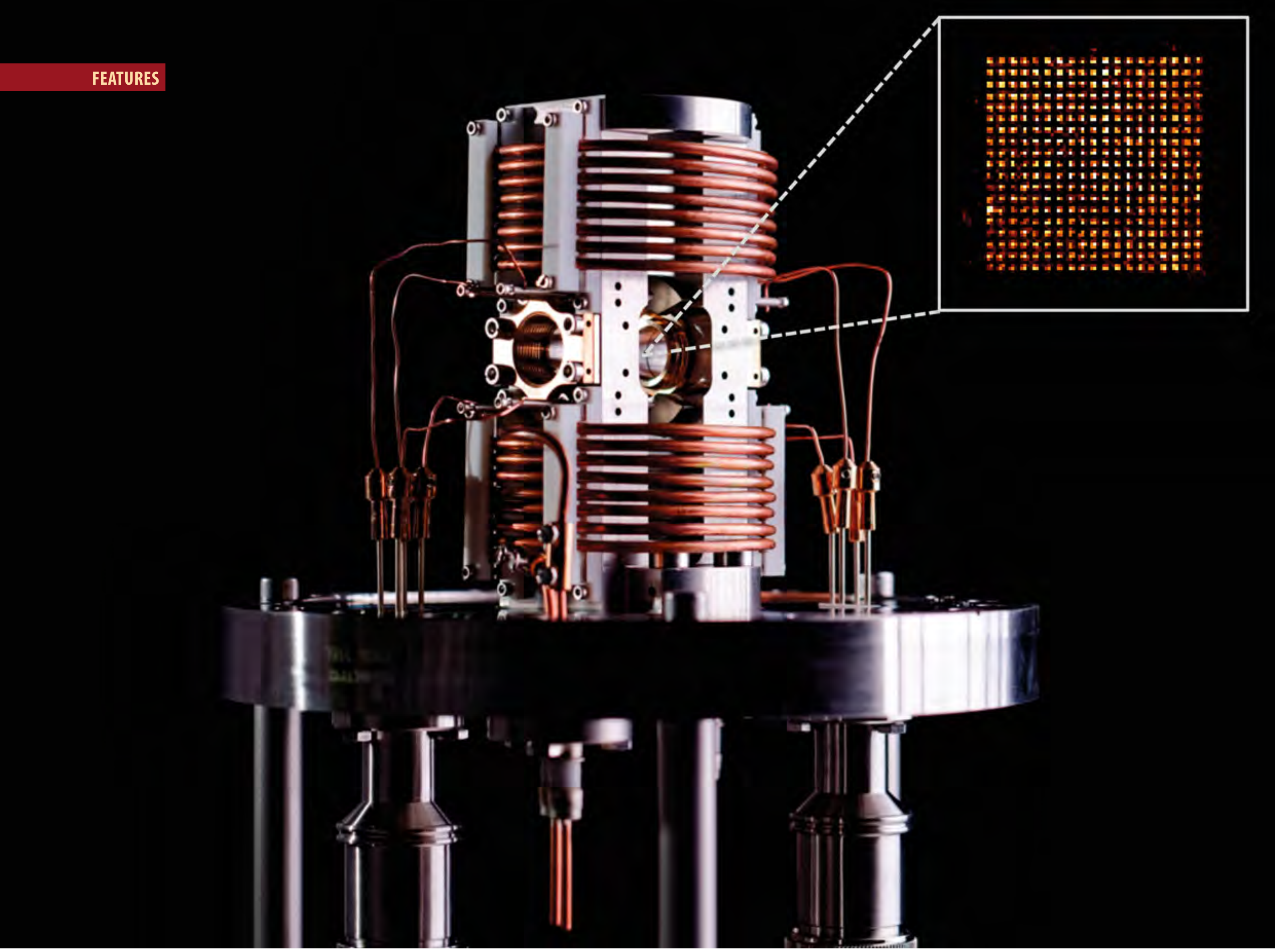


QUANTUM SIMULATION AND COMPUTING WITH ARRAYS OF SINGLE RYDBERG ATOMS

Thierry Lahaye[1] and Daniel Barredo[2] – DOI: https://doi.org/10.1051/epn/2022406

[1] Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127 Palaiseau, France

[2] Nanomaterials and Nanotechnology Research Center (CINN-CSIC), Universidad de Oviedo (UO), Principado de Asturias, 33940 El Entrego, Spain

Over the last years, a new platform for quantum technologies has emerged. It is based on arrays of single atoms arranged with almost arbitrary geometries, and made to interact by exciting them to Rydberg states. Compared with other platforms, such as trapped ions or superconducting qubits, atom arrays are quite competitive for applications such as quantum simulation of magnetism. We describe the experimental methods used in this field, and illustrate recent applications.

Since the 1980s, one can manipulate individual quantum objects (electrons, ions, photons…), and realize what was previously thought to remain *Gedankenexperimente*, for instance the demonstration of entanglement. Over this period, it has also been realized that harnessing the laws of quantum mechanics for practical applications, such as cryptography or computing, could lead to a second quantum revolution, with new and extremely efficient approaches to solving some problems. To do so however, one needs to exquisitely control large assemblies of quantum objects.

Even if the realization of a fully-fledged quantum computer remains a formidable task, tremendous progress has been made recently in manipulating larger and larger assemblies of quantum objects. One of the earliest applications of these systems will be *quantum simulation*: the realization of many-body systems governed by Hamiltonians usually studied in condensed-matter physics. Here, we describe one of the most appealing platforms for quantum simulation of spin Hamiltonians encountered in magnetism, namely arrays of single atoms with programmable geometries, and that interact strongly when excited to Rydberg states. We first describe the tools used to realize this platform, and then illustrate its use through recent experiments.

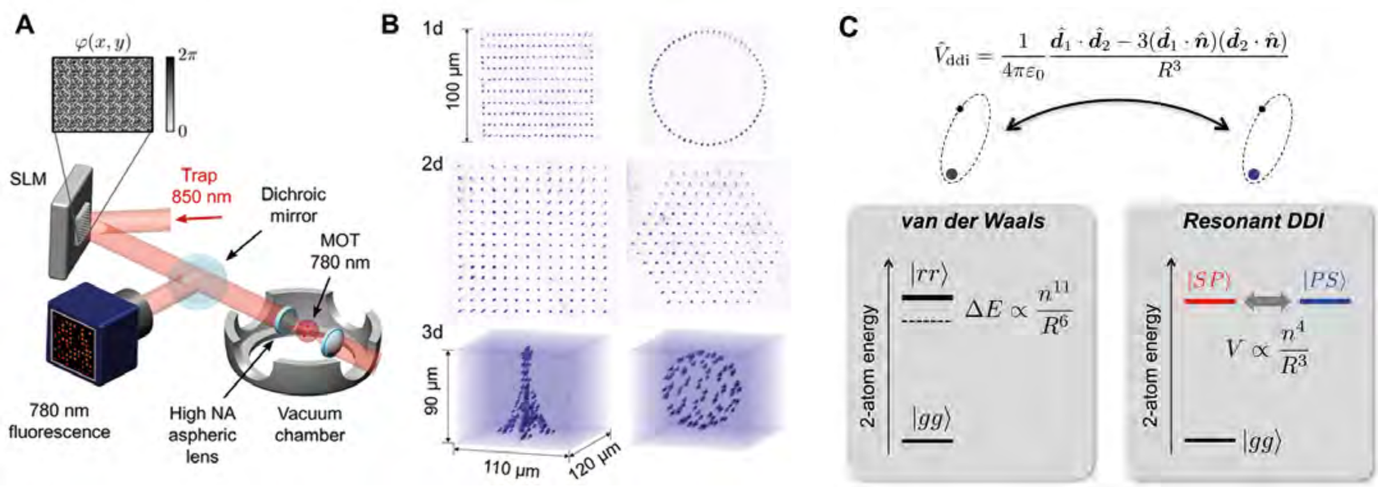
Experimental tools

Single atoms in optical tweezers were pioneered by the group of P. Grangier at Institut d'Optique in 2001 [1]. His team demonstrated that by tightly focusing a laser beam it is possible to create trapping volumes so small that, under certain conditions, only one atom fits inside. These optical tweezers are created with high-numerical-aperture optical systems, and a few milliwatts of light are enough to trap atoms from a magneto-optical trap (MOT). The atoms can be detected by fluorescence using the same optics that focuses the tweezers. During loading, when an atom enters the microtrap, it is further cooled down and stays trapped; whenever a second atom is loaded, a fast light-assisted collision takes place, leading to the loss of both atoms. This prevents the simultaneous presence of two atoms in the trap, but the loading is stochastic with an occupation probability of about 50%.

This can be extended to a larger number of traps with holographic methods (Fig. 1a). By imprinting an appropriate phase in the trapping beam with a spatial light modulator (SLM), a single trap can be replicated into hundreds of traps, each of them hosting at most one atom [2]. For a long time, the non-deterministic loading of the arrays hindered the use of this platform for quantum simulation. Since 2016, a simple approach has been broadly adopted to overcome this limitation. It consists in actively sorting the atoms in the arrays with dynamical optical tweezers. This assembling process obtains filling fractions near unity, and one can currently generate two- and three-dimensional [3] defect-free arrays containing more than 200 atoms with almost arbitrary geometries (Fig. 1b).

The spacing in these arrays is typically a few micrometers. At these distances, ground-state atoms hardly interact. To reach strong interactions, atoms are thus laser-excited to Rydberg levels, *i.e.* states with a principal quantum number $n >> 1$, where the size of the electronic orbit scales as n^2. These giant atoms thus exhibit very large electric dipole moment also scaling as n^2, responsible for strong dipole-dipole coupling between atoms (Fig. 1C). This coupling can give rise to either a van der Waals shift (for identical Rydberg levels, the interaction then scales as n^{11}/R^6, where R is the distance between the two atoms), either to a resonant dipolar interaction where atoms coherently exchange their internal states (for opposite parity Rydberg levels, the exchange frequency scaling as n^4/R^3). These tunable interactions reach tens of megahertz at distances of a few micrometers, thus setting sub-microsecond timescales for the dynamics, much shorter than the lifetimes of Rydberg states.

◂ **P. 28:** The heart of the experiment: high-NA aspheric lenses, magnetic coils, and control electrodes are held together inside an ultra-high vacuum chamber. Inset: fluorescence emitted by an array of 361 rubidium atoms. The lattice spacing is 5 µm.



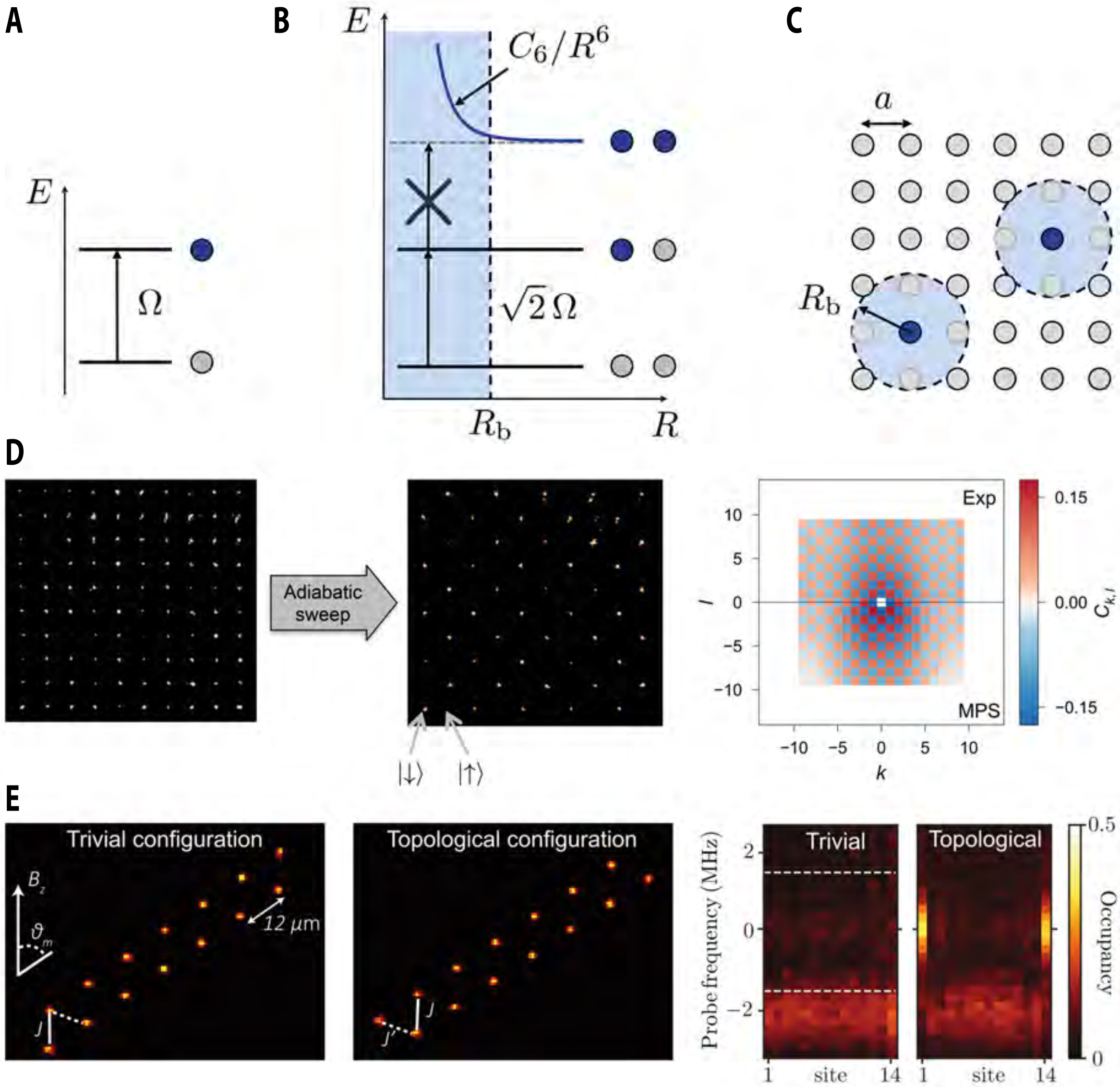
▾ **FIG. 1:** Experimental tools. a) Sketch of the experimental setup. b) Examples of arrays of single atoms. c) The electric dipole-dipole interaction (DDI) between Rydberg atoms can give rise to different types of interactions (see text).

Quantum simulation of spin models

These interactions can be harnessed to realize strongly correlated quantum states. A basic concept at play for this is *Rydberg blockade*. Consider first a resonant laser, driving an atom with a Rabi frequency Ω, and making it oscillate between the ground and Rydberg states (Fig. 2a). For two atoms separated by a distance smaller than the *blockade radius* R_b, only one of the two atoms can be excited, as the doubly excited state is shifted out of resonance by van der Waals interactions (Fig. 2b). This mechanism is central for creating entanglement and realizing two-atom quantum gates.

In a large array where the lattice spacing a is comparable to R_b, many atoms can be Rydberg-excited, but those excitations are strongly correlated (Fig. 2c). One can show that, if we encode spin states in the ground and Rydberg states, the Hamiltonian describing the combined effect of laser driving and of van der Waals interactions is equivalent to the quantum Ising model used in quantum magnetism, that describes arrays of spins interacting with $J_{ij}\sigma_i^z\sigma_j^z$ interaction terms between spins i and j (σ^z denotes the Pauli matrix). The laser plays the role of an external magnetic field. One can adiabatically prepare the many-body ground state of this system (Fig. 2d). Starting with all atoms in $|\downarrow\rangle$ (left) and slowly varying the amplitude and frequency of the laser, one excites only every second atom due to the Rydberg blockade, resulting in a checkerboard pattern (middle), which is nothing but an antiferromagnet. The right panel in Figure 2D shows the spin-spin correlation function $C_{k,l}$ for a 10 × 10 array, measured on the system (top) and calculated using state-of-the-art numerical techniques such as Matrix Product States (MPS), showing excellent agreement and validating the quantum simulator. For our system sizes of ~200 spins, even approximate numerical simulations of the dynamics become intractable [4].

The platform can also be used to implement 2D XY spin models, where the spins rotate in a plane and now interact via an interaction $J_{ij}(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y)$. To do so, one encodes the spin states in opposite-parity Rydberg levels, and the dipolar interaction gives couplings $J_{ij} \propto 1/R^3_{ij}$. The role of magnetic fields is mimicked here by microwaves. Interestingly, XY magnets are equivalent to systems of hard-core bosons, where bosons can hop around a lattice,



▸ **FIG. 2:** Quantum simulation of spin Hamiltonians. A, B, C: Principle of the Rydberg blockade: the van der Waals interaction C_6/R^6 prevents the simultaneous Rydberg excitation of two nearby atoms. D: Adiabatic preparation of an Ising antiferromagnet using van der Waals interactions. E: Observation of edge states in a Su-Schrieffer-Heeger chain. The topological and trivial chains differ only by the position of one atom, making the chain start either with a strong coupling J or with a weak one J'. This translates in a drastic change in the eigenstates of the system, with zero-energy edge states appearing only for the topological configuration.

but with an occupancy that cannot exceed one on a given site. We have used such an approach to study interacting topological matter [5] in a Su-Schrieffer-Heeger chain (Fig 2e). Topological matter can also be explored using the Ising Hamiltonian: recently, a $\mathbb{Z}_2$ spin liquid, an intriguing state of matter with exotic properties, has been realized [6].

Future developments

Rydberg arrays based on alkali atoms such as rubidium (Rb) or caesium (Cs) have become an almost ideal platform for quantum simulation of spin models. They already allow investigating non-trivial phases of matter. More recently, the use of tweezers arrays has been extended to other species such as strontium [7] or ytterbium, with promising applications also in metrology. The platform is obviously very appealing for quantum computing; gates based on the Rydberg blockade have seen their fidelities improve steadily.

The current interest in quantum technologies has led to the emergence of several companies in the US and in Europe that aim at developing Quantum Processing Units based on Rydberg arrays and making them available on the cloud to scientists and industrial users. There is no doubt that widespread access to such machines will lead to exciting developments. ■

About the authors

Thierry Lahaye is a CNRS scientist at Institut d'Optique. He is an experimentalist and has worked for twenty years in atomic physics. Since 2012, in the group led by Antoine Browaeys, he has applied the Rydberg array platform to quantum simulation of spin models. He is also a co-founder of the company Pasqal.

Daniel Barredo is a Ramón y Cajal Research Fellow at CSIC, where he continues his research on Rydberg atom arrays, after having worked for more than eight years with Thierry Lahaye and Antoine Browaeys at the Institut d'Optique on these topics.

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Last minute shuffle: the International Physics Olympiad 2022

Because of the Russian war against Ukraine and the role of Belarus in the conflict, the organisers of the International Physics Olympiad (IPhO) cancelled this year's competition in Minsk.

Fortunately, at the last minute Switzerland stepped in and organised this year's International Physics Olympiad as an online event. The 52st IPhO was saved! About four hundred high school students from 75 countries participated in the Olympiad which took place 10-17 July, 2022. Belarus and Russia were not invited as nations, but students from these two countries could participate under a neutral flag.

As usual, many teams received medals and honourable mentions (https://ipho2022.com/results). The Chinese team was most successful with the best overall score for Guowei Xu and the highest scores in experiment and theory for Mingxuan Yang and Qiancheng Li, respectively.

The annual International Physics Olympiad offers high school students the opportunity to establish professional contacts at national and international level at an early stage. The participants compete in national teams for several days in solving challenging experimental and theoretical physics problems that go far beyond the school curriculum.

In his welcome words, the president of the IPhO encouraged the participating students: “May you all always carry the torch of knowledge into the future, wherever you go.”

In 2023, IPhO will be organised by Japan in Tokyo.

▾ The Ukrainian team

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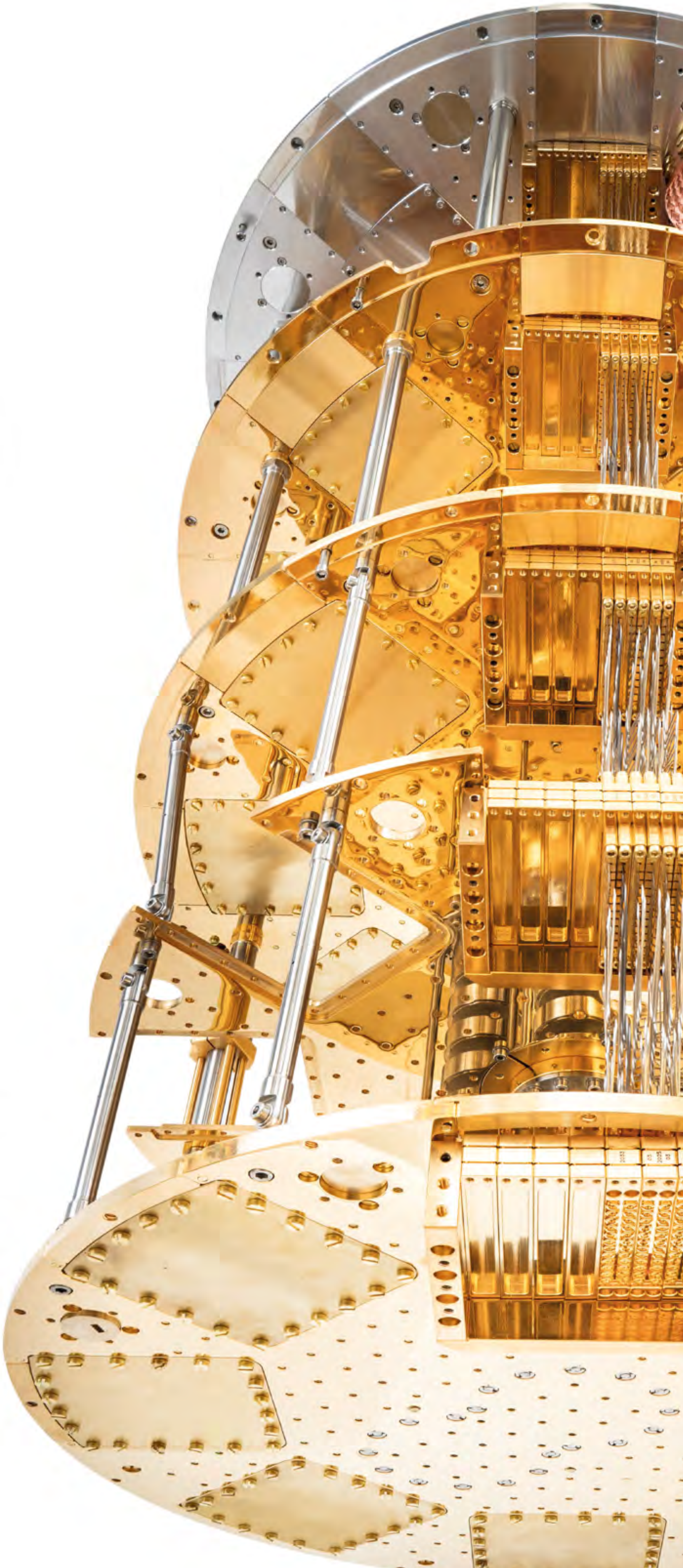

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