europhysicsnews

X-ray phase contrast imaging
Nuclear masses and the origin of the elements
Is the Mexican wave really a ripple of excitation?
Alexandru Proca (1897-1955) and his equation
Density waves in atomic necklaces

37/5
2006
Volume 37 • number 5
Institutional subscription price:
99 euros per year

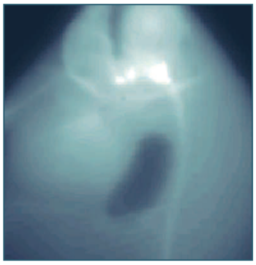
European Physical Society
EDP SCIENCES

PUB

europhysicsnews

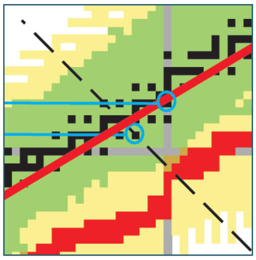
2006 • Volume 37 • number 5

cover picture: neither mexican nor density but wave anyway.
image courtesy: Shaun Quinlan (shaunjquinlan@mail.com) - www.morguefile.com - A large ocean swell arrived on our coast overnight, this mutated wave crashing onto the beach of Homunga Bay.



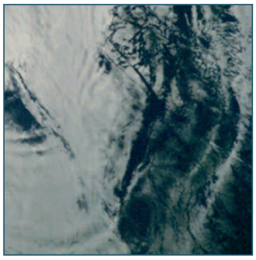
▲ PAGE 13

X-ray phase contrast imaging using a grating interferometer



▲ PAGE 16

Nuclear masses and the origins of the elements



▲ PAGE 22

Is the Mexican wave really a ripple of excitation?

EDITORIAL

HIGHLIGHTS

NEWS

FEATURES

PUB

europhysicsnews

2006 • Volume 37 • number 5

europhysicsnews is the magazine of the European physics community. It is owned by the European Physical Society and produced in cooperation with EDP Sciences. The staff of EDP Sciences are involved in the production of the magazine and are not responsible for editorial content. Most contributors to europhysicsnews are volunteers and their work is greatly appreciated by the Editor and the Editorial Advisory Board. europhysicsnews is also available online at: **www.europhysicsnews.com**
General instructions to authors can be found at : www.eps.org/publications.html

ISSN 0531-7479
ISSN 1432-1092 (electronic edition)
Printer Printer Rotofrance • Lognes, France
Dépôt légal: Septembre 2006

editorial

Open access: a new paradigm in science publication?

The "currency" of science has traditionally been scientific publications, evaluated by peers and published in high prestige scientific journals. This has been the traditional way of disseminating scientific results. This is a publication tradition that has been tremendously successful and scientific journals have witnessed a rapid growth.

There are, however, other currencies, real money for one. This more traditional currency has definite advantages in that it can be traded more freely than scientific knowledge. This other currency also becomes important because scientific knowledge carries with it a value outside the science system itself.

This is why many countries have put forward new legislation to better quantify the value of scientific discoveries. We talk about the patent system. The patent system is a proprietary system, that restricts access to, often important, scientific research, discoveries and know how. This will have an impact on the science publication business, which is motivated by industry's desire to exploit scientific discoveries and the need to justify to politicians and to the society who want to see a return on its investment in scientific research, and the funds allocated to university and institutional research infrastructure.

This is a sharp departure from the traditional justifications for publicly supported science, which were to take care of your research and good care of your students. These very same students were the physical outcome of the research enterprise when they left academia and went into society carrying with them the newest knowledge about a certain field of science.

The result is clear. Scientists and in particular physicists with their strong influence on novel technologies are put in an impossible situation, one side the desire to publish one's results as openly and visibly as possible and, on the other side to exploit novel results of great commercial value.

It is in such times, further mediated by rising costs of publications and the massive growth of scientific publications, that the open access forum has launched an effort (see document p.4) to

- implement a policy to require their researchers to deposit a copy of all their published articles in an open access repository and
- encourage their researchers to publish their research articles in open access journals where a suitable journal exists and provide the support to enable that to happen."

The open access ideas are supported by close to 200 research organizations among them the very large organizations running well known large scale facilities. The open access principles are universal and most of us can without hesitation subscribe to them. However, it is not enough to convince oneself of the virtues of open access.

It is also necessary to recognise the value of traditional publications and the scientific publishing business, and that the journals published do much more than make research results available. It adds value to publications through peer review, distribution, referencing, archiving, promotion etc. Authors, researchers, universities, and research institutes benefit from this added value and from the prestige of these journals. Career development and financing are closely tied to articles published in traditional journals, and this system, albeit open to criticism, does offer a relatively objective indicator of the value and pertinence of the published research.

Moreover, our "owners", national governments and other funding agencies, invest in science for more than expanding human knowledge. In order for open access to prove its merits it will be necessary to document its strength as an innovation driver as compared to the traditional ways of disseminating scientific knowledge through publications, often following a period of •••

··· non-disclosure in order for patents and licensing to take place.
The European Physical Society is a publisher. Therefore the discussion raised by the open access movement is of great importance to our society and our sister societies around the world. We are involved in many discussions to define our goals and objectives to sustain a viable physics publishing community.

Scientific publishing is critical to all of us. Our libraries carry accumulated information and have for centuries proven their worth in doing so. Learned societies, like the EPS and academic publishers, have likewise proven their worth in publishing scientific results and making their publications available to their membership, libraries and other interested readers. The competitive and lucrative nature of scientific publishing have made it possible for commercial publishers to prosper as well.

We all agree that scientific publishing is important. But the added value comes at a cost. At present, the subscription model is used, i.e. the reader pays. For open access to become a viable alternative to traditional publishing, it is necessary to closely look at the costs and decide who should pay. Open access needs to show that it can provide all of the benefits of traditional publishing and meet changing political demands, e.g. drive innovation. And the mentality of the researchers, institutions, and funding agencies need to change. The EPS will play its role in animating the debate and in this way contribute to the validation of the ideas behind open access and repositories of scientific articles freely to be accessed by scientists. ■

Ove Poulsen, EPS President.

A document on Open Access

The delegates of the "Berlin 3 Open Access Conference" (Feb 28th - Mar 1st, 2005, University of Southampton, UK) agreed on a guide to the implementation of the Berlin Declaration.

Preamble

The signatories of the Berlin Declaration are committed to achieving full open access to scholarly communication in order to realize the benefits of world-wide access to knowledge. In order to implement the Berlin Declaration institutions should

- Implement a policy to require their researchers to deposit a copy of all their published articles in an open access repository.
- Encourage their researchers to publish their research articles in open access journals where a suitable journal exists and provide the support to enable that to happen.

Where we start from

- The opportunity for universal access to the results of academic research provided by the availability of the internet and the www
- The superior capabilities of the digital medium for scholarly communication
- The need for rigorous quality assessment of research
- The benefits from the inter-connection of publications with immediate access to primary source data
- The academic community's need to drive future developments in scholarly communication.

Where we aim to be

- The publication of the work of researchers according to the principles of open access as defined in the Berlin Declaration
- The evaluation of open access content according to the highest standards of quality assurance
- The universal availability of a comprehensive source of human knowledge and cultural heritage that has been approved by the academic community.

First steps along the road (already taken)

- The definition of goals in the Berlin Declaration
- The commitment of signatory organizations to promote the goals identified in the Berlin Declaration
- The announcement of the Berlin Declaration together with an invitation to other research organizations to declare their support
- The design of a "roadmap" to assist organizations in planning their strategy in relation to the principles of the Berlin Declaration
- BUT many more steps need to be taken to achieve the Berlin Declaration goals
- These steps are a mix of immediate, medium-term and long-term actions.

Raising awareness

- The design of an advocacy programme for internal communication within organizations addressed to researchers, to organizational leaders, and to research administrators
- The advocacy programme should identify the value added to the organization's work through the implementation of open access
- Communication of the goals of the Berlin Declaration to political players together with a call for financial and legal conditions favourable to open access
- Encouragement to learned societies to support open access through permissions to deposit articles in repositories or through the conversion of journals to an open access business model.

Organizational policy

- Each organization committing to the goals of the Berlin Declaration should formulate a policy identifying the steps to be taken in implementing the goals
- The policy should include steps which can be taken by all members of the organization's research staff to deposit research articles in the organizational repository with minimal additional time and effort on the part of the researcher
- The policy should also include financial support for the organization's research staff in meeting publication-charges for open access journals.

Creating a sustainable infrastructure

- Organizations (both institutional and subject-based) committing to open access should establish an open web-site repository into which their researchers may deposit copies of journal articles and research reports
- The repository should be compliant with international standards for interoperability such as OAI-PMH and in particular use a metadata structure which meets the needs of the research community
- Quality assurance procedures should be adopted indicating to the reader the status of items in the repository
- The repository should adopt preservation techniques to ensure the long-term availability of the content it contains

- Appropriate search and retrieval tools should be adopted to facilitate access to the repository content
- Trustworthy statistics should be kept of the use of the repository content and incorporated in the organization's research evaluation exercises
- A sustainable financial and administrative structure should be set up for the organizational repository.

Establishing a legal framework

- A legal framework should be established for the organizational repository governing the relationship with authors, publishers and users of the repository content
- The organization should make clear to researchers its policy on deposit in the repository, whether mandatory or recommended
- A scholarship-friendly licence such as Creative Commons should be adopted to govern the relationship with authors and with users of the content
- Publishers should be asked to accept the terms of the licence adopted by the repository for content they have published
- The liability for any infringement of third party rights should be set out in the licence adopted.

Supporting open access journals

- The recognition within an organization's research strategy that the dissemination of research results is an indispensable element in the research process
- Signatory organizations may consider encouraging the use of research grants to pay open access publication-charges for their researchers
- Support for learned society publishers willing to transition to an open access business model
- Support for research into a business model ensuring the long-term viability of open access journals.

Long-term organizational commitment

- Ensure that the Berlin Declaration principles are built into the organizational strategy
- Create a group or committee to oversee the organizational commitment to open access
- Assign specific responsibilities to specific members of staff
- Build repository costs and open access journal support into the organizational budget
- Maintain contact with other organizations implementing the Berlin Declaration and participate in working groups established to exchange experience on open access procedures and developments.

Removing the barriers on the way

- Much has been achieved but much more remains to be achieved before we can say that we are close to reaching the goals set out in the Berlin Declaration
- We need to understand where the barriers lie
- Author motivation? (make deposit as easy as possible and make open access "respectable")
- Institutional motivation? (demonstrate benefits to the institution)
- Political support? (form alliances with powerful allies)
- Publisher/learned society fears? (demonstrate that open access is no threat to their survival)
- Barriers need to be removed at every stage along the road but the Berlin Declaration goals can be achieved through action by the research community at an organizational and at an individual level. ■

March 2005

Highlights from european journals

A theory to shorten plane boarding

The authors have applied 2-D Lorentzian Geometry to a familiar problem for travellers everywhere. They have assessed various boarding policies employed by international airline carriers to minimise passenger waiting times. They have gone on to recommend the optimal process which is shown to be a combination of the standard back-to-front boarding with an element of randomness.

This research will be of interest to mathematical and theoretical physicists and the wider scientific community due to its relevance to everyday life. ■

E. Bachmat, **D. Berend**, **L. Sapir**, **S. Skiena** and **N. Stolyarov**, "Analysis of aeroplane boarding via spacetime geometry and random matrix theory" *J. Phys. A: Math. Gen.* **39** L453 (2006)

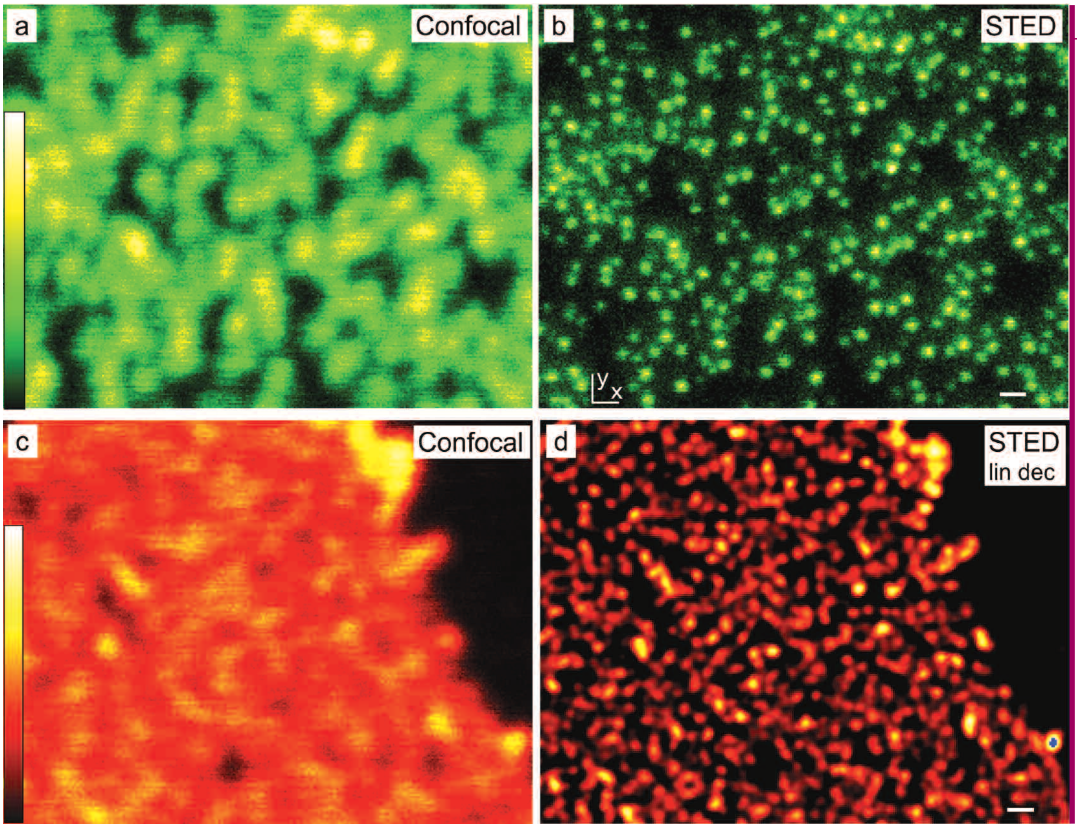
Diffraction-unlimited far-field optical microscopy resolves fluorescent nanoparticle assemblies

Abbe's discovery of the diffraction barrier about 130 years ago has lead to the common notion that a light microscope cannot resolve spatial structures that are closer than about half of the wavelength of light. Near-field optical microscopy overcomes this limit by scanning with a subdiffraction sized tip, but this technique is difficult to operate and is limited to imaging surfaces.

Stimulated emission depletion (STED) microscopy is the first *far-field* fluorescence microscopy modality which, although still relying on regular lenses and visible light, radically overcomes the limiting role of diffraction. In fact, the resolution Δr of a STED microscope follows a new law given by $\Delta r \cong \lambda/[2n \sin \alpha\,(1+\zeta)^{1/2}]$, where λ and $n \sin\alpha$ are the wavelength of light and the numerical aperture of the lens, respectively. The equation differs from Abbe's famous resolution law by the square-root term in the denominator, where $\zeta >>1$ defines the magnitude of STED. Evidently, letting $\zeta\rightarrow\infty$ implies that the resolution can be improved down to the molecular scale.

The emerging power of STED-microscopy is is exemplified by revealing the spatial order of densely packed biological and non-biological nanopatterns. Unlike confocal microscopy, which is the best-resolving standard used in the far-field, STED microscopy resolves fluorescent nanoparticles that are of 40 nm diameter (λ/15) as well as nanosized aggregates of a neuronal protein in a cell membrane [1]. Similarly, images of colloidal nanoparticles demonstrate the potential of STED-microscopy for colloidal physics. Finally, we show the first STED microscopy images obtained records images of protein distributions in a cell with regular lenses and visible light, that feature a resolution that is about the size of biological macromolecules twice the size of an antibody (20 nm) [Donnert G, *et al*: *PNAS* **130** (2006) 114402]. ■

K.I. Willig, **J. Keller**, **M. Bossi**, **S.W. Hell:**
"STED microscopy resolves nanoparticle assemblies'assemblies", *New J Phys.* **8**, 106 (2006).

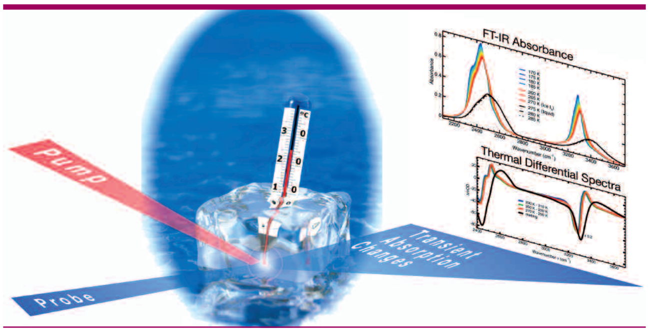


◀ Defying Abbe's law in lens-based optical microscopy. Whereas the confocal microscopy image **(a)** renders blurred patches, the image provided by STED-microscopy **(b)** resolves every 40 nm bead in a densely packed agglomeration. Panels **(c)** and **(d)** compare confocal with STED imaging (plus linear deconvolution) of the neuronal protein SNAP-25, naturally agglomerated in a cell membrane. The fundamentally increased spatial resolution brought about by STED microscopy holds great promise for addressing fundamental issues in many areas of physics, chemistry, and biology.

Experimental test of Anderson localization theory

Anderson predicted in 1958 that waves diffusing through a disordered, three-dimensional medium should come to a halt at some critical amount of disorder [Anderson, *Phys. Rev.* **109** (1958) 1492]. This phase transition is due to constructive interference of waves propagating on reciprocal multiple scattering paths. Because the path has the same length in both counter-propagating directions, the probability of returning to the starting point is increased twofold and hence transport is hindered. This is called weak localization. At high disorder, when the mean free path becomes comparable to the wavelength, the multiple scattering paths form closed loops leading to a phase transition where diffusion breaks down. While this concept has had many applications in solid-state physics, photonics and acoustics, there has not yet been an unequivocal experimental verification of the existence of the localization transition. This is because in electronic systems, electron-electron interactions or bound states may similarly lead to a metal-insulator transition. In optical systems however, such effects are absent. Nevertheless, static transmission or reflection measurements cannot distinguish between localization and absorption. Using time resolved measurements of light diffusion in highly scattering materials we have now provided clear experimental evidence for the existence of a transition to Anderson localization of visible light [Störzer *et al.*, *Phys. Rev. Lett.* **96** (2006) 063904]. In particular there is an increase of photons traversing the sample at late times (see Figure). This slowing down of diffusion is consistent with the rescaling of the diffusion coefficient predicted by scaling theory more than 25 years ago [Abrahams *et al.*, *Phys. Rev. Lett.* **42** (1979) 673]. In addition, the deviations from diffusion can be used to determine the length scale on which photons are localized as the phase transition is approached. This gives a measurement of the critical exponent of scaling theory. Such experimental information on the critical exponent is of great importance in the theoretical controversy concerning the properties of the localization transition. ■

C.M. Aegerter, M. Störzer and G. Maret,
"Experimental determination of critical exponents in Anderson localisation of light" *Europhys. Lett.*, **75**, 562 (2006).



▲ A picosecond pulse is passed through a powder of TiO_2 (the inset shows a scanning electron micrograph of the sample). The localization of photons on closed loops leads to a slowing down of transmission as indicated by the non-exponential tail in the time of flight distribution (main figure). The red line is a fit to diffusion theory with a rescaled diffusion coefficient ($D(t) \propto t^{-1}$ as required by localization, whereas the dashed blue line corresponds to classical diffusion.

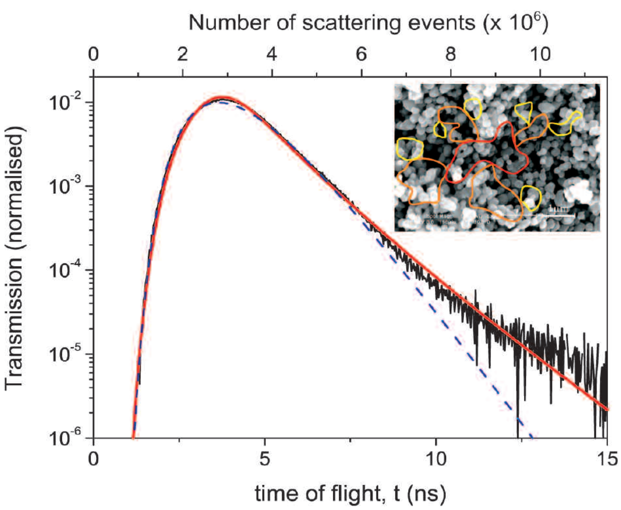
Picosecond jumps of temperature and pressure in ice

Water in its liquid and solid phase is ubiquitous for human life. Almost every physical and chemical process in an aqueous material strongly depends on temperature and pressure. An increasing interest for studying such processes on shorter timescales makes it also necessary to have a sensitive probe of transient thermodynamic quantities on an ultra-short timescale.

The present paper demonstrates a novel spectroscopic method to measure temperature and pressure changes of an ice sample on the picosecond timescale. The technique can be extended to other hydrogen-bonded systems. The method utilizes the pronounced temperature and pressure dependency of the absorption band of the hydroxilic stretching vibration. The effect is due to the strong coupling of the OH vibration to the hydrogen bonds between the molecules. The sample is heated by sub-picosecond IR laser pulse. The temporal evolution of temperature and pressure in the sample is determined by comparing the time-resolved absorption changes conventional IR absorption. Here it is important to consider the isochoric character of the ultra-fast temperature jump of constant volume leading to a pressure increase.

The amplitude and the spectral shape of the steady-state differential spectra for a fixed temperature jump depend only slightly on initial sample temperature since the spectral position shows a nearly linear dependency on initial temperature. The feature allows the extrapolation of the steady-state thermal differential spectra above the melting point and measurement of a possible transient superheating of the sample.

The method is verified for isotopic mixtures of ice at 200 K and ambient. The results show that the use of a temperature scale is meaningful for ice as early as 20 ps after the energy deposition. Using this technique for measurements close to the melting point a superheating of the ice lattice up to 25°C without melting for more than 1.3 ns was observed for the first time. ■



M. Schmeisser, A. Thaller, H. Iglev and A. Laubereau,
"Picosecond temperature and pressure jumps in ice" *New J. Phys.* **8**,104 (2006)

Figure: Cartoon of a pump-probe experiment for measuring picosecond temperature and pressure changes in ice.

Collaboration in physics between China and Europe

An agreement of collaboration between the Chinese Physical Society (CPS) and EPS was signed on 6 July 2006 in the EPS Secretariat in Mulhouse, during the visit there by Prof. Enge Wang and Ms Dongmei Gu, the Secretary General and Associate Secretary General of the CPS. EPS President Ove Poulsen welcomed the guests to the Secretariat and added his signature to that of CPS President Guozhen Yang on the Agreement and the CPS and EPS Secretaries General then signed a document regarding the implementation of the Agreement.

The Agreement sets in motion an exchange of Invited Speakers between CPS and EPS: starting in 2007, EPS will send a Delegate to the annual Fall Meeting of the Chinese Physical Society. CPS, on the other hand, will every year send an Invited Speaker to one of the major Europhysics conferences. Given the rapid development of physics in China, it will be useful to have regular live reports by suitable EPS-sponsored Chinese speakers at European conferences. Moreover, one may expect that the CPS Fall Meeting will, in due course, acquire global importance, accordingly, it is valuable that EPS helps to maintain the European profile there.

The EPS–CPS Agreement also involves the exchange of information on important events and conferences between the two societies as well as an exchange of conference proceedings and of their membership magazines *Europhysics News* and *Physics*.

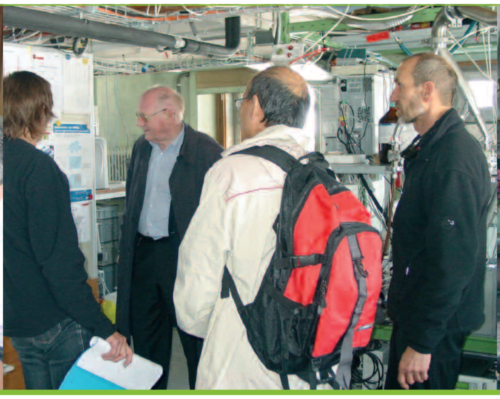
▲ Enge Wang, CPS Secretary General and EPS President Ove Poulsen, holding with the Agreement following its signature.

Following the signing ceremony, the Chinese guests, accompanied by EPS representatives, paid a visit to the President of the *Université de Haute Alsace* (*UHA*), Prof. Guy Schultz, and ended the morning touring the *CNRS Laboratoire de Physique et Spectroscopie Electronique* at *UHA*, guided by its Director, Prof. Carmelo Pirri. In the afternoon, the Chinese visitors and EPS personnel and Executive Committee members discussed informally a wide range of topics.

Before their visit to Mulhouse, the Chinese delegation visited Zurich, Bern, the Jungfraujoch and Basel. Prof. Enge Wang, who is Director of the Physics Institute of the Chinese Academy of Sciences — the highest-rated Physics Institute in China — gave talks at two research labs: one at EMPA, the materials science and technology research institution in Dübendorf near Zurich, which belongs to the ETH domain, and the other at the National Center of Competence in Research (NCCR) for Nanoscale Science, which is led by the Physics Institute of the University of Basel. The trip to the High Altitude Research Station on Jungfraujoch took place on 4 July 2006 — on the day of the 75th anniversary of this institution! This excursion was rewarded both by providing an impression of the range of projects, particularly in atmospheric chemistry and physics that are carried out at the station, and by the experience of the magnificient Alpine world, albeit one couldn't avoid noticing the evidence of global warming in the fragile environment up there. The stay in Bern included a tour of the Einstein Exhibition in the Historical Museum with Peter Jezler, the creator of this impressive exhibition, as well as a dinner with some of the physicists working in the city, where Albert Einstein lived through his *annus mirabilis* 101 years ago.

The Agreement now signed represents a concrete step toward expanding the horizon of EPS. I would hope that the collaboration will be intensified in the years to come. ■

Martin C.E. Huber,
Vice-President of the EPS



▲ **Fig. 1:** Delegations of CPS and EPS visited visiting the President of the *Université de Haute Alsace*, *UHA* (from left to right: EPS Secretary General David Lee, former EPS President Martin Huber, 1st *UHA Vice-Président/Politique Internationale* Prof. Michel Faure, *UHA Président* Prof. Guy Schultz, CPS Secretary General Prof. Enge Wang, EPS President Ove Poulsen, former EPS Executive Secretary Peter Melville and Director of the *CNRS/UHA Laboratoire de Physique et Spectroscopie Electronique* Prof. Carmelo Pirri).

Fig. 2: Martin Huber and Enge Wang in the laboratory of the High Altitude Research Station Jungfraujoch, where instruments for measuring aerosols that influence atmospheric warming and cooling are located.

Fig. 3: Associate CPS Secretary General Dongmei Gu, with former and current EPS Presidents Martin Huber and Ove Poulsen in front of the fortification wall around the church of Eguisheim — the historic Alsatian village, where a farewell dinner was held.

Leibinger Prizes in laser physics and applications

By awarding prizes every two years, the Berthold Leibinger Foundation, founded by its present chairman of the board, B. Leibinger (TRUMPF GmbH + Co. KG), wishes to promote laser technology – one of the most important technologies of our time – and help make it available to the public.

Internationally announced and endowed with a total of 35,000 Euros, the Berthold Leibinger Innovation prizes award and promote scientists and developers who are pioneers in the field of laser light. The Berthold Leibinger Zukunftspreis honors forward-looking innovations in research for the application or generation of laser light with a prize money of 20,000 Euros.

Awarded for the first time, the **Zukunftspreis** went to Prof. **H. Jeffrey Kimble** from the California Institute of Technology in Pasadena, California, USA, for forward-looking innovations in laser technology. The jury felt Kimble's research in cavity quantum electrodynamics will change the future.

The usual 2006 Berthold Leibinger **Innovationspreis** were awarded in the following order. Drs. **Karin** and **Raimund Schütze**, co-founders of P.A.L.M. GmbH in Bernried, Germany, won first place with their laser micro-tool for capturing individual cells. The P.A.L.M. Microlaser Technologies GmbH has been a part of the Carl Zeiss Group since the end of 2004. Prof. **Ian A. Walmsley** from Oxford University, UK, accepted the second prize for the SPIDER measuring method to characterize ultrashort laser pulses. The third prize went to Dr. **Michael Mei** and Dr. **Ronald Holzwarth** of Menlo Systems GmbH in Martinsried, Germany, for the development of compact laser systems with the optical frequency comb technique. ■

More details on www.leibinger-stiftung.de

Science in public areas

After the great success of the International Year of Physics in 2005, the European Physical Society developed, in collaboration with Hisa Eksperimentov, the project "Science in Public Areas" whose purpose is to promote science awareness within the wide public, through attractive series of questions and answers, displayed in public areas.

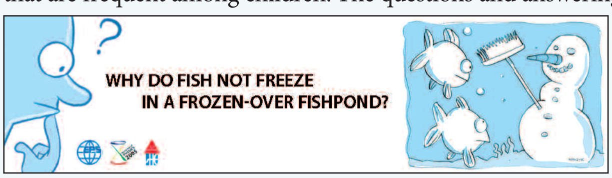
Project aims

Several studies confirm that young people are losing interest in science studies for the following reasons:
- science looks too hard,
- poor image of scientists
- Lack of awareness of scientific careers.

The objectives of "Science in Public areas" are:

- to help rebuild the public impression of physics and physicists;
- explain simply and in an amusing manner some basic principles in physics;
- increase the awareness and excite the curiosity of the general public and young people in particular.

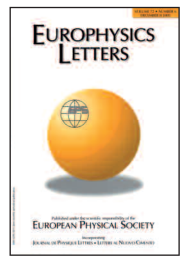
Posters with the physics questions and answers will be placed in public areas, such as theme parks, public transport, schools and science centres. The answers are short, attractive, informative and scientifically correct. They can give an answer to questions that are frequent among children. The questions and answering illustrations will draw the public attention. EPS provides you with the files: questions, answers as well illustrations in PDF formats.



Partners:

I f you wish to display the posters, they are available in English, French and German. If your organisation wishes to contribute to the project or becomes an Associate Member of the EPS, your logo can be put on the posters. For more information, please **contact Mrs Ophélia Fornari**, Project Leader for EPS activities, o.fornari@eps.org – or by phone +33 389 329 448. ■

Nominations for Editor in Chief of EPL



Nominations are requested for the Editor in Chief of EPL, a letters journal owned and published by a consortium of national physical societies. The Editor in Chief (EiC) needs to be a recognised authority and leading researcher in a field of physics, and have a broad knowledge and interest in physics and its frontiers. The EiC will need to demonstrate strong commitment and leadership to developing EPL into a top-ranking journal. To this end, a proven ability to interact with senior scientists is required. Experience with the editorial process for a physics journal is also essential. The EiC will play a key role in making EPL a leading global physics letters journal with high impact and high visibility that publishes high-quality articles across all of physics. The term of office of EPL Editor in Chief is three years. A job description is available at www.epletters.net.

Nominations may be made by the individual concerned, or by third parties not later than **31 October 2006**. Nominations should include a CV, publication list and a brief covering letter explaining their interest and qualifications for the post of the person being nominated. Nominations should be sent to the chair of the selection committee care of the EPL Editorial Office (editorial.office@epletters.net). ■

EPS session in Ukraine (June 2006)

The joint session of the Executive Committee of EPS and Ukrainian Physical Society (UPS) was held during 22-25 June 2006 in Kiev. It was also attended by representatives of the National Academy of Sciences of Ukraine (NASU), the Ministry of Science and Education (MSE), Universities and other organizations.

It is important to note that this meeting was initiated by the EPS (now it unites 30 national physics associations from Europe) with the aim to strengthen contacts of the physics communities of Europe and Ukraine.

Physics is important in many areas in society and the economy, for example playing an essential role in technological progress in electronics, computer sciences, communications, etc. The World year of Physics in 2005 highlighted many of these achievements and looked not only at past successes in physics, but at future challenges. The joint session considered possible actions to continue the promotion of physics.

In the opening ceremony, introductions were given by the president of EPS, O. Poulsen, the counsellor of President of Ukraine, I.R. Yukhnoski, the Vice-president of NASU, A.G. Naumovets, the head of the division of physics of NASU, V.M. Loktev, and the president of UPS, V.G. Litovchenko.

The Executive Committee of the EPS during its session discussed at length the plans by the EU to establish a European Institute of Technology. One of the main issues is whether the EIT will be one institution with clear localization or a confederation of the institutions placed in different countries. In order to better integrate Ukrainian scientists, the Ukrainian physicists present supported the second view and proposed to involve Ukrainian institutions in this activity.

Summary of the other main presentations made by the participants.

President EPS, Prof. O. Poulsen

Physics is undergoing great changes. On a European scale, there is much pressure to change how we do science, with for example the creation of the ERC centralising funds for frontier research.

Another challenge for physics comes from the Bologna process to coordinate curricula, harmonise degrees and promote mobility. One of the problems with this process however is that physics does not really have a 1st cycle leading to a degree with employment opportunities.

In the countries represented here today, their different cultural heritage, their phase of economic development, and the needs of their society have an impact on all elements of scientific research. One of the most basic needs is the development of a strong research infrastructure.

The EPS sees Ukraine as part of Europe and we look forward to receiving input on the problems related to physics education and research in order to develop adequate policies for the integration and promotion of physics in this area.

Prof. Shopa, editor of the UPS journal World of Physics

The UPS journal "World of Physics" was created in 1997 and is a collaboration of the UPS, the Academy of Sciences, the Shevchenko Scientific Society, and the Ministry of Education and Science. The journal covers items of general interest, scientific features, and book reviews. As there are few publications in the Ukrainian language, it is important to support them.

◄ President of EPS, O. Poulsen and president of UPS V.G.Litovchenko, during the joint session.

Prof. V. Yashchuk (Nat.Kiev.Uni.), Head of Executive Council of UPS

The UPS was founded in 1990. It played an important role in the struggle for independence and democracy in the Ukraine. It currently has 620 members in 41 regional and local groups. Its main activities include the organisation of conferences, dissemination of information to its members and to the public, and the provision of expert advice on projects and installations.

The main problems faced by physics and physicists in the Ukraine include the improvement of salary and working conditions for physicists in Europe. The current salary for a professor is approximately 300€/month. Equipment needs to be modernised as well.

Prof. A. Zagorodnii, Editor of Ukr. Phys. Zh and Dr. O. Shopa, "The state and problems of Ukrainian physics publications—and potential solutions"

Scientists in Ukrainian research institutes publish approximately 4000 papers/yr in journals all over the world. EPS support for publication in Ukraine is very important and EPS recognition of some of the new journals would be helpful.

M. Stepko , representative of Education Ministry and ex-president of UPS, Prof. V. Baryakhtar "On the state of physics education in the Ukraine — where are changes needed"

In the Ukraine, physics education in university is targeted towards the deliverance of Masters and PhD degrees. There are currently 1150 physics students in Kiev. Degrees in more practical and applied aspects of physics are being studied. University education in the Ukraine has been adapted to conform to the ECTS requirements to improve student and teacher mobility. Interdisciplinary studies are being promoted as well.

The Ukraine too is confronted with the problems of the Bologna process, and the lack of a real 1st level university degree in physics.

There is a problem in finding employment for graduates. Physics studies are not attractive if there are no jobs, and funding for the faculties is related to the number of students. The laboratories cannot hire the graduates, and there is no work in the industrial sector either.

Pre-university physics education depends on the high school and whether the student will study science at university. For these high schools concentrating on physics, students have 5 hours of physics per week. The main problem is equipment, and the Ukraine currently has a programme with Germany to provide equipment.

During the cold war, it was easier to find students and funding for physics education. However, this has changed and assuring the next generation of physicists is a big problem. Access to good textbooks and an adequate supply is needed.

S. Ryabchenko
The number of members is relatively low because the UPS had few activities in the recent past. There has been much brain drain in Ukraine. One solution is the "shuttle scientist", who works 1-2 years abroad, and returns to the Ukraine afterwards, and keeps good contacts and collaborations in other countries. The Ukraine has also received much international support (*e.g.* APS, the Soros Foundation, EPS ...). These actions have helped to stabilise science in the country. Physics plays a leading role: 39% of all scientific papers in the Ukraine are in physics. International assistance is still required. The EPS could advocate that levels of intellectual and scientific activity be taken into account of integration/development of FSU. The EPS could reduce the membership fees for scientists in FSU countries. The EPS could look at new ways to combat the brain drain, and work with the FSU countries on the implementation of the Bologna process.

▲ President of EPS, O. Poulsen and vice-president of EPS, M. Huber during the session.

Oleksandr Slobodyanyuk
The UPS is a bottom-up initiative, and one of the first manifestations of civil society in the Ukraine. It is unprecedented as a non-profit, non-governmental association. Its creation introduced elementary notions of democracy and opened the eyes of other people and served as a model for other professional societies. One of the main roles of the UPS has been to act as a clearing house for funds from international aid programmes. ■

Call for nominations: IBA-Europhysics prize 2007
for applied nuclear science and nuclear methods in medicine

The Nuclear Physics Board of the EPS invites nominations for the year 2007 for the IBA-Europhysics prize. The award will be made to one or several individuals for outstanding contributions to Applied Nuclear Science and specially Nuclear Methods and Nuclear Researches in Medicine.

The Board would welcome proposals which represent the breadth and strength of Applied Nuclear Science and Nuclear Methods in Medicine in Europe.

Nominations should be accompanied by a filled nomination form, a brief curriculum vitae of the nominee(s) and a list of major publications. Letters of support from authorities in the field which outline the importance of the work would also be helpful.

Nominations will be treated in confidence and although they will be acknowledged there will be no further communication. Nominations should be sent to: **Selection Committee IBA Prize**
Chairman Prof. Ch. Leclercq-Willain ,
Department of Theoretical Nuclear Physics – PNTPM – CP 229Université Libre de Bruxelles, Boulevard du Triomphe, B1050 Bruxelles, Belgium
Phone: +32 (0)26505560
Fax: +32 (0)26505045
E-mail: cwillain@ulb.ac.be

For nomination form and more detailed information see the web site of the Nuclear Physics Division: www.kvi.nl/~eps_np and the web site of EPS: www.eps.org (EPS Prizes, IBA-Europhysics Prize)

Deadline for submission of the proposals: 15.01.2007. Sponsored by Ion Beam Applications, Belgium

General description of the prize

The European Physical Society (EPS), through its Nuclear Physics Board (NPB) shall award a Prize to one or more researchers who have made outstanding contributions to Applied Nuclear Science and specially Nuclear Methods and Nuclear Researches in Medicine (investigation, aid to diagnosis and/or therapy).
Such contributions shall represent the breadth and strength of Applied Nuclear Science and Nuclear Methods in Medicine in Europe.

Regulations

1/The Prize shall be awarded every two years
2/The Prize shall consist of a Diploma of the EPS and a total prize money of 5000 € (to be shared if more than one laureate)
3/The money of the prize is provided by the Belgian Company IBA (Ion Beam Applications)
4/The Prize shall be awarded to one or more researchers
5/The Prize shall be awarded without restrictions of nationality, sex, race or religion
6/Only work that has been published in refereed journals can be considered in the proposals for candidates to the prize
7/The NPB shall request nominations to the Prize from experts in Nuclear Science and related fields who are not members of the Board. Call for nomination will be published in Europhysics News, Nuclear Physics News International, and at the homepage of the IOP journal "Physics in Medicine and Biology".
8/Self-nominations for the award shall not be accepted
9/Nominations shall be reviewed by a Prize Committee appointed by the NPB. The Committee shall consider each of the eligible nominations and shall make recommendations to the NPB, taking also into account reports of referees who are not members of the Board.
10/The final recommendation of the NPB and a report shall be submitted for ratification to the Executive Committee of the EPS. ■

Lise Meitner prize for nuclear science 2006

The European Physical Society awarded through its Nuclear Physics Board the Lise Meitner Prize for Nuclear Science 2006 to Professor **David Brink** (Emeritus Fellow, Balliol College, University of Oxford, UK) and Professor **Heinz-Jürgen Kluge** (Gesellschaft für Schwerionenforschung, Darmstadt, Germany). Medals, diplomas and cheques, sponsored by CANBERRA, France, were presented to the two Laureates at a special ceremony at the Seventh International Conference on Radioactive Nuclear Beams (RNB7) in Cortina d'Ampezzo, Italy, on July 7, 2006.

David Brink is honoured for his many contributions to the theory of nuclear structure and nuclear reactions which have helped to shape Nuclear Physics over several decades. He is one of a select band of theorists whose work over more than forty years has deeply influenced the field. His seminal work with D Vautherin in 1969-1971 on a theory of nuclear masses using effective interactions of the Skyrme type in a mean- field approach proved particularly successful and established the ground rules for thousands of papers in nuclear theory. This work introduced density functional methods into nuclear many-body theory and has been cited over 1150 times, including 30 in 2003. His methods are currently being used by theorists all over the world in the new field of exotic nuclei.

Brink's 1972 work on transfer reactions between heavy ions is also heavily cited by both theorists and experimentalists. Based on semi-classical ideas, this work provided a useful simple way of understanding and predicting important selection rules for transfer reactions.

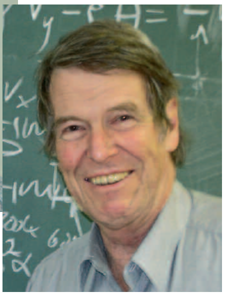
Brink's ideas and insights have also helped to clarify a variety of other phenomena including nuclear giant resonances, clustering in nuclei and quantum-mechanical and semi-classical theories of heavy-ion scattering. With C V Sukumar and others he showed how the Feynman Path Integral approach to quantum effects could be applied successfully to nuclear reactions.

Brink's work reflects his remarkable intuition, his clarity and ability to simplify the description of complicated phenomena by identifying the most appropriate approximations. He has had a large number of students and collaborators from all over the world. For all of them he has been a source of scientific and human inspiration and admiration. His commitment to the value of truth and his unselfish attitude to sharing knowledge have made him an outstanding figure in nuclear physics and one still very active at the frontline of research.

Heinz-Jürgen Kluge has enriched our knowledge of the masses, sizes, shapes and spins of nuclei through a number of decisive, sophisticated and brilliant experiments combining techniques of atomic and nuclear physics. He is honoured for his key contributions to these developments.

As a young post-doctoral researcher in the early 1970's he set up an optical pumping experiment on a chain of neutron deficient mercury isotopes at ISOLDE, CERN, and measured their spins, moments and charge radii. Recently, backed by the huge progress in laser techniques and isotope production, he initiated a heroic experiment to measure the tiny shifts in the atomic spectra of Li-isotopes produced by the different nuclear volumes of the isotopes. The same technique was used successfully to measure the size of the very exotic halo nucleus 11Li, so-called because of the way some of its neutrons are distributed far outside the protons. His application of laser spectroscopic trace analysis to the study of environmental 90Sr after the Chernobyl disaster earned him the prestigious Helmholtz award in 1990.

◄ Professor David Brink



► Professor Heinz-Jürgen Kluge

Kluge's development of the ISOL-trap for the precision mass measurement of nuclear masses is well known. His exploitation of this method has led to the readjustment of the nuclear mass scale over large regions of the nuclear chart far from stability, and his precise determination of beta-decay properties have led to fundamental tests of weak interaction theory. This method is now applied worldwide, often by Kluge's pupils, or with their support. As head of the relevant GSI-group he has also pushed the complimentary Schottky mass measurements in the storage ring ESR.

Heinz-Jürgen Kluge's experimental ideas and achievements have had an invaluable impact on the art of experimental atomic and nuclear physics, and his results for nuclear ground-state properties have provided a reliable and indispensable cornerstone for nuclear theory. He has inspired at least 55 PhD students with his physics skill and enthusiasm, many of whom are active in science and academia. ■

▼ Lise Meitner Prize Ceremony
from left to right: Ron Johnson, David Brink, Heinz-Jürgen Kluge, Hartwig Freiesleben

Hartwig Freiesleben,
Technische Universität Dresden
Chairman, Nuclear Physics Board

X-ray phase contrast imaging using a grating interferometer

Franz Pfeiffer [1], Timm Weitkamp [2], and Christian David [1]
[1] Paul Scherrer Institut • 5232 Villigen PSI • Switzerland • [2] Forschungszentrum Karlsruhe • 76021 Karlsruhe • Germany.

In conventional x-ray imaging, contrast is obtained through the differences in the absorption cross section of the constituents of the object. The technique yields excellent results where highly absorbing structures, *e.g.*, bones, are embedded in a matrix of relatively weakly absorbing material, *e.g.*, the surrounding tissue of the human body. However, in those cases where different forms of tissue with similar absorption cross-sections are under investigation (*e.g.*, mammography or angiography), the x-ray absorption contrast is relatively poor. Consequently, differentiating pathologic from non-pathologic tissue from an absorption radiograph obtained with a current hospital-based x-ray system still remains practically impossible for many tissue compositions.

To overcome these limitations, several methods to generate radiographic contrast from the phase shift of x-rays passing through the sample have been investigated in recent years [1-3]. They can be classified into crystal interferometer methods, techniques using an analyzer, and free-space propagation methods. Although some of them yield excellent results for specific problems, none is very widely used. In particular, none of them has so far found medical diagnostics applications, which require a large field of view of many centimeters, the efficient use of broadband radiation as provided by laboratory X-ray generators and a reasonably compact setup.
As an alternative approach we have recently developed a grating based differential phase contrast (DPC) setup which can efficiently be used to retrieve quantitative phase images with polychromatic x-ray sources of low brilliance [4]. Some of the recent results are reviewed in the following.

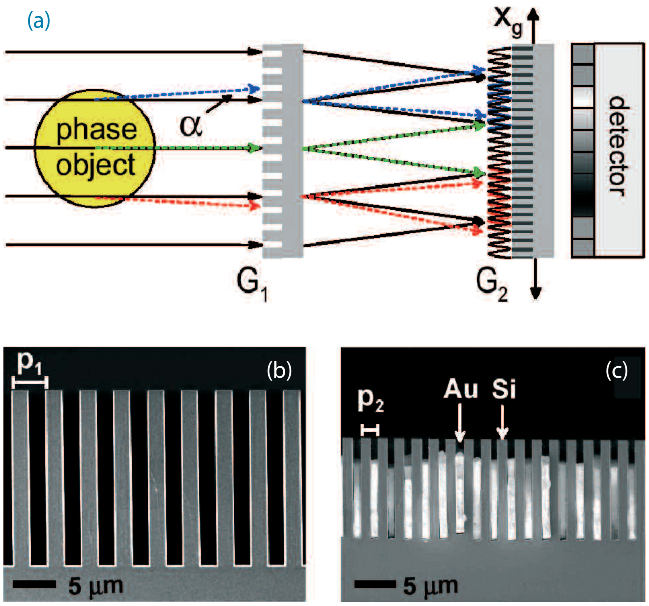
Principles of Grating Interferometry

A setup for grating based DPC imaging essentially consists of a phase grating G1 and an analyzer absorption grating G_2 (Fig. 1a). The DPC image formation process is similar to differential interference contrast (DIC) microscopy used with visible light. It essentially relies on the fact that a phase object placed in the x-ray beam path causes slight refraction of the beam transmitted through the object. The fundamental idea of DPC imaging depends on locally detecting these angular deviations (Fig. 1a). The angle, α, is directly proportional to the local gradient of the object's phase shift and can be quantified by [5]

$$\alpha = \frac{\lambda}{2\pi}\frac{\partial\Phi(x,y)}{\partial x} \qquad (1)$$

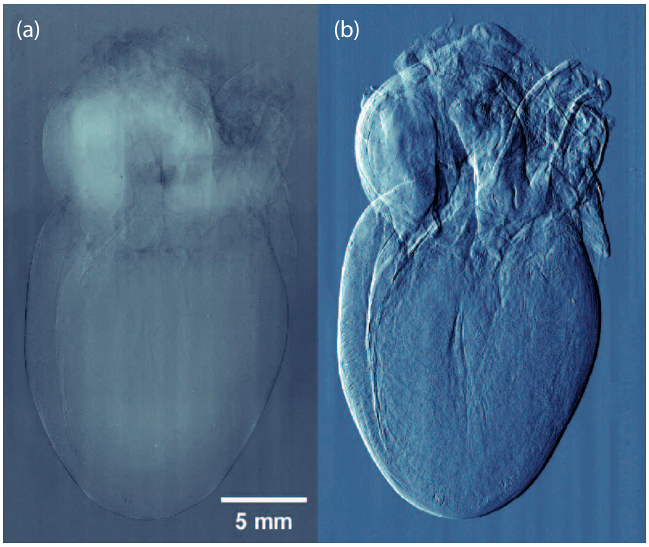
where x and y are the Cartesian coordinates perpendicular to the optical axis, $\Phi(x,y)$ represents the phase shift of the wave front, and λ the wavelength of the radiation. For hard x-rays, with $\lambda < 0.1$ nm, the angle is relatively small, typically of the order of a few micro radian.

In our case, determination of the angle is achieved by the arrangement formed by G_1 and G_2. Most simply, it can be thought of as a multi-collimator translating the angular deviations into changes of the locally transmitted intensity, which can be detected with a standard imaging detector. For weakly absorbing objects, the detected intensity is a direct measure of the object's local phase gradient $d\Phi(x,y)/dx$. The total phase shift of the object can thus be



▲ **Fig. 1:** **(a)** Principles of a hard x-ray imaging interferometer. A phase object in the beam path causes a slight refraction for each coherent subset of x-rays, which is proportional to the local differential phase gradient of the object. This small angular deviation results in changes of the locally transmitted intensity through the combination of gratings G_1 and G_2. A standard x-ray imaging detector is used to record the final images. **(b, c)** Scanning electron micrograph cross sections of the gratings fabricated by photo lithography, wet chemical etching and electroplating of gold.

▼ **Fig. 2:** X-ray images of a rat heart obtained at a highly brilliant x-ray synchrotron source (ESRF, Grenoble).
(a) Conventional X-ray transmission image. **(b)** Differential phase contrast image.



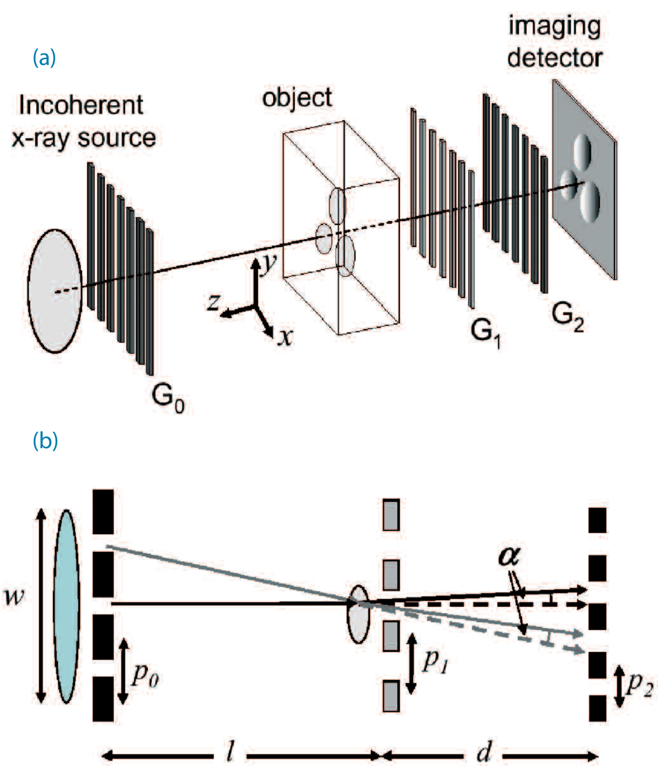
retrieved by a simple one-dimensional integration along x. As described in more detail in [6], higher precision of the measurement can be achieved by splitting a single exposure into a set of images taken for different positions of the grating G_2.

X-ray Synchrotron Results

In a first step, the method described was tested using a highly brilliant x-ray synchrotron beam produced by an undulator source at the European Synchrotron Radiation Facility (ESRF, Grenoble, France). As an example, Figure 2 shows the results for an animal organ, a rat heart, which was placed in a container filled with a 4% aqueous formalin solution. For the experiments monochromatic x-rays of 17.5 keV have been used. In the conventional absorption contrast image (Fig. 2a), only faint details of the fatty tissue and some contrast from the edges of the object are visible. The complete organ with many details on the detailed blood vessel structure can be seen in the differential phase contrast image (Fig. 2b). As is shown in more detail in [5] the DPC images can be quantified and extended to a three-dimensional imaging method by recording projections of the sample for different angles in combination with computer tomographic reconstruction algorithms. In such a way three- dimensional phase images with a resolution of a few micrometers were obtained.

Into the clinics?

A prerequisite for methods aiming towards clinical x-ray applications is that they should work with standard and commercially available x-ray generators, and not only with highly brilliant and partially coherent X-rays from a synchrotron. As we have shown recently [4], in this particular aspect the grating interferometer is superior to already existing phase-sensitive techniques, because it can be adapted for low-brilliance sources. The trick is to use an *arrayed source* [7], and the easiest way to realize this is by using a *third* grating (G_0) just behind the source, as illustrated in Figure 3.



▲ **Fig. 3:** (a, b) Setup for x-ray tubes. Using a third grating, efficient use can be made of a standard, low-brilliance x-ray tube generator with large source sizes.

Since the source mask G_0 can contain a large number of individual apertures, each creating a sufficiently coherent virtual line source, efficient use can be made of standard x-ray generators with source sizes of more than a square millimetre [4]. To ensure that each line source produced by G_0 contributes constructively to the image formation process, the geometry of the setup should satisfy the condition (Fig. 3b)

$$p_0 = p_2 \times \frac{l}{d} \qquad (2)$$

It is important to note that the total source size w only determines the final imaging resolution, which is given by wd/l. It does not affect contrast or efficiency, as would be the case for most other phase-sensitive methods.

Figure 4 displays the results of applying our method to a biological object, a small fish (*Pterophyllum scalare*) using a standard, laboratory based x-ray tube generator. The conventional x-ray transmission image is shown in Fig. 4a, while Fig. 4b contains a greyscale image of the corresponding DPC signal. Since both images were extracted from the same data set, the total exposure time, and thus the dose delivered to the sample was identical in the two cases. The field of view in this case is 50 x 50 mm^2. As expected, the skeleton of the fish and other highly absorbing structures, such as the calcified ear stones (*otoliths*) are clearly visible in the conventional radiograph (Fig. 4a). However, small differences in the density of the soft tissue, *e.g.*, the different constituents of the eye, are hardly visible in conventional absorption image. In the corresponding DPC image (Fig. 4b), they are clearly visible. We observe that in particular smaller structures with higher spatial frequencies, e.g. the fine structure of the tail fin, are better represented in the DPC image than in the corresponding absorption radiograph.

Conclusion & Outlook

These recent results represent a major step forward in radiography with standard x-ray tube sources that could provide all of the information imparted by conventional radiography, with additional information on soft tissue. This may prove to be of clinical importance, particularly in the detection of soft tissue pathologies. This hope is further supported by the fact that DPC methods generally exhibit advantages in the imaging of tumor masses with relatively slow variations of the integrated phase shift if compared to other phase contrast imaging methods, *e.g.*, free space propagation [8].

Due to the fact that the results have been obtained with a standard, relatively low-cost and commercially available x-ray tube generator, we envision a widespread application of our method in areas where phase imaging would be desirable, but is currently unavailable. For example, we believe that this method can readily be implemented without major changes to currently existing medical imaging systems, particularly in the view of the ease of fabricating large-area gratings using standard photolithography, the high resistance of the method against mechanical instabilities, and the possibility to use detectors with large pixels and a large field of view. Since phase contrast imaging does not intrinsically rely on the absorption of x-rays in material, the radiation dose can potentially be reduced by using higher x-ray energies. Furthermore, we envisage applications in the field of non-destructive testing, such as, *e.g.*, the characterization of surface non-uniformities of reflective x-ray optics [9]. Finally, these results open up the way for phase imaging experiments using other forms of radiation, for which only sources of relatively low brilliance currently exist, as for example beams of neutrons [10] or atoms [11]. ■

Acknowledgements:
We gratefully acknowledge the help of O. Bunk, C. Kottler, J. Bruder, E. Ziegler, and P. Cloetens. This work was partly supported by the KTI under contract 7796.2 DCPP-NM.

About the authors:
Franz Pfeiffer studied Physics at the University in Munich. During his PhD he worked on X-Ray and neutron waveguides at the Institut Laue Langevin and the European Synchrotron Radiation Facility (ESRF) in Grenoble. Since then he is leading a research group on coherent x-ray scattering at the Paul Scherrer Institut (PSI).

Timm Weitkamp studied Physics at the University of Hamburg. He received his PhD in 2002 for a thesis on high-resolution microtomography and hard X-ray microscopy at the ESRF. After a PostDoc stay at the PSI, he is now a beamline scientist at the ANKA light source operated by Forschungszentrum Karlsruhe

Christian David studied Physics at the University of Göttingen. During his PhD, he worked on x-ray microscopy and nanolithography techniques. After a PostDoc stay at the Institute for Applied Physical Chemistry, University of Heidelberg, he joined the PSI where he presently leads the X-ray Optics and Applications Group.

References

[1] R. Fitzgerald, *Physics Today* **53**, 23 (2000).

[2] A. Momose, *Optics Express* **11**, 2303 (2003).

[3] A. Momose, *Jap. Jour. Appl. Phys.* **44**, 6355 (2005).

[4] F. Pfeiffer, T. Weitkamp, O. Bunk, and C. David, *Nature Physics* **2**, 258 (2006).

[5] T. Weitkamp, A. Diaz, C. David, F. Pfeiffer, M. Stampanoni, P. Cloetens, and E. Ziegler, *Optics Express* **13**, 6296 (2005).

[6] T. Weitkamp, A. Diaz, B. Nöhammer, F. Pfeiffer, T. Rohbeck, P. Cloetens, and C. David, *Proc. SPIE* **5535**, 137 (2004).

[7] C. David, F. Pfeiffer, and T. Weitkamp, *European patent application* 05012121.9 / EP05012121 (2005).

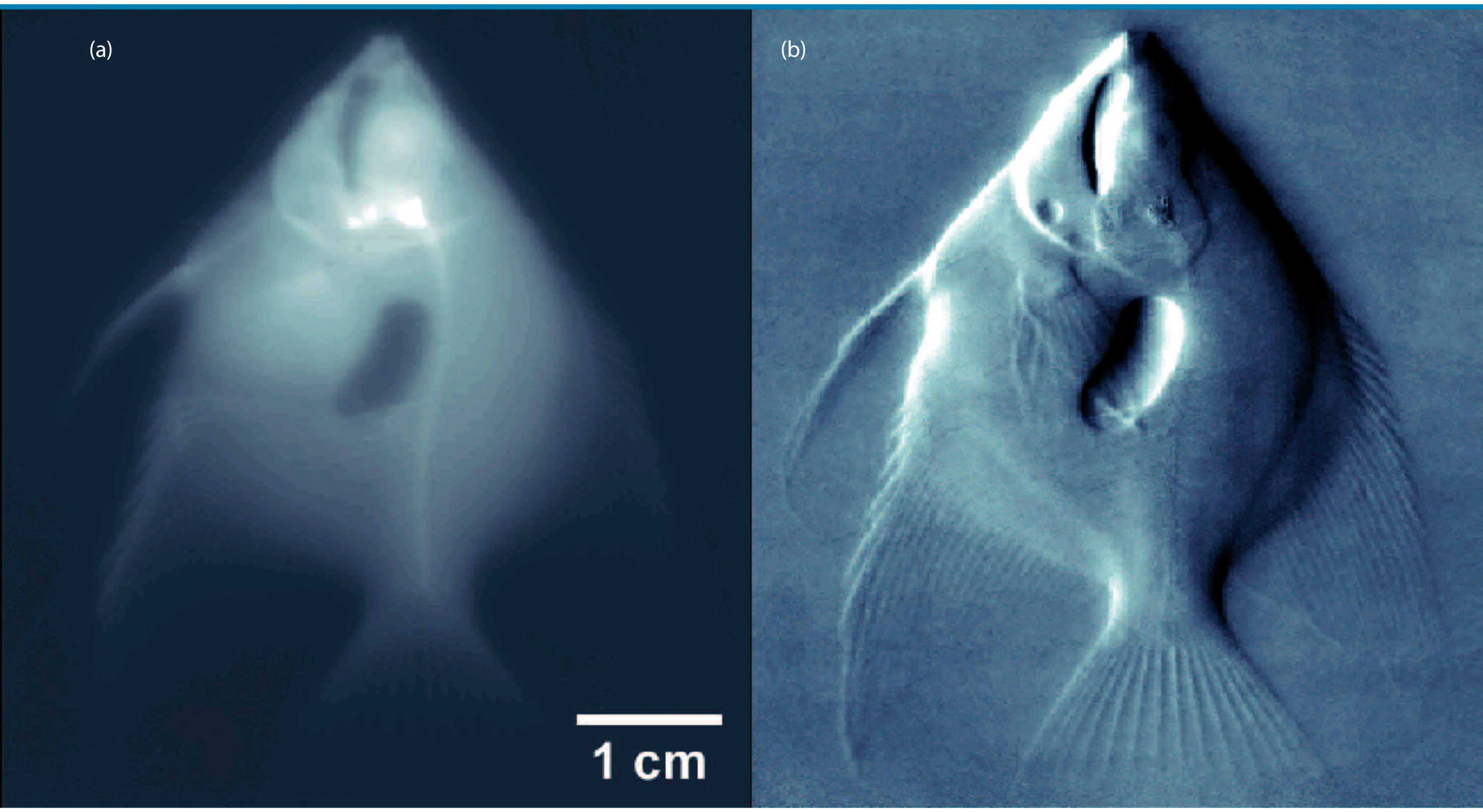
[8] E. Pagot, S. Fiedler, P. Cloetens, A. Bravin, P. Coan, K. Fezzaa, J. Baruchel, and J. Härtwig, *Phys. Med. Biol.* **50**, 709 (2005).

[9] T. Weitkamp, B. Nöhammer, A. Diaz, C. David, and E. Ziegler, *Appl. Phys. Lett.* **86**, 054101 (2005).

[10] F. Pfeiffer, C. Grünzweig, O. Bunk, G. Frei, E. Lehmann, and C. David, *Phys. Rev. Lett.* **96**, 215505 (2006).

[11] D.W. Keith, C.R. Ekstrom, Q.A. Turchette, and D.E. Pritchard, *Phys. Rev. Lett.* **66**, 2693 (1991).

▼ **Fig. 4:** X-ray images of a small fish retrieved from image data recorded with a standard x-ray tube operated at 40 kV/ 25 mA. (**a**) Conventional X-ray transmission image. (**b**) Differential phase contrast image. The total exposure time was 200 seconds.

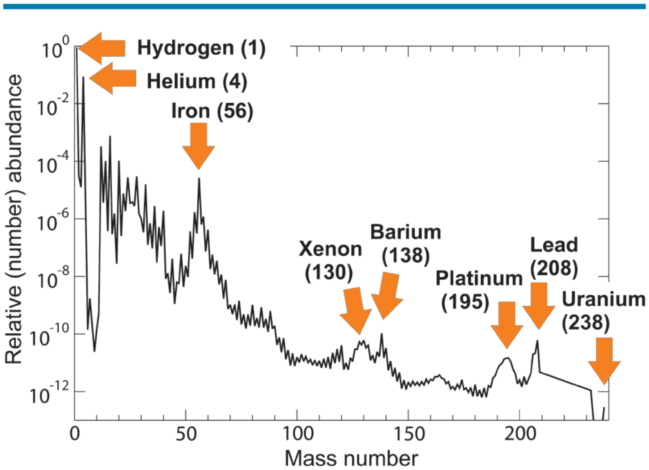


Nuclear masses and the origin of the elements

Hendrik Schatz [1], Klaus Blaum [2]
[1] Johannes Gutenberg-University Mainz and GSI Darmstadt • Germany.
[2] National Superconducting Cyclotron Laboratory, Michigan State University • USA.

The chemical composition of our universe has many surprising features: why does the sun consist of mainly hydrogen and helium? Why is iron so much more abundant than heavier elements such as gold? Why are there heavy elements at all and how did they come into existence? The properties of atomic nuclei, especially their masses, play a crucial role in these fundamental questions at the interface of nuclear and astrophysics.

Fig. 1 shows the distribution of the solar system isotopic abundances determined from the analysis of meteorites and the spectrum of sunlight. Many of the general features of the distribution of the solar system elemental abundances shown in Fig. 1 can be found throughout our Galaxy and probably the universe as a whole, though there are variations owing to differences in nucleosynthetic history or ongoing nucleosynthesis processes. Hydrogen and helium are by far the most abundant elements in the solar system. These elements were already produced in the big bang, together with traces of lithium. All the heavier elements must have been created after the big bang by nuclear processes, mostly in stars and stellar explosions. A look at the nuclear masses explains why the big bang was not able to produce heavy elements using the already formed hydrogen (^{1}H) and helium (^{4}He). Among the possible nuclear fusion reactions one could imagine are the fusion of two hydrogen nuclei into ^{2}He, the fusion of a hydrogen nucleus with a helium nucleus producing ^{5}Li, or the fusion of two helium nuclei into ^{8}Be. ^{2}He, ^{5}Li, and ^{8}Be have one thing in common: in contrast to the isotopes usually found on earth and in stars these nuclei have extremely short lifespans - for example, in the case of ^{8}Be the average lifetime is just 10^{-16} seconds. The reason is that the decay of these nuclei into fragments is energetically possible because the total mass of the fragments is smaller than the mass of the nucleus itself. This mass difference corresponds according to Einstein's famous equation $E = mc^2$ to the binding energy that can be released during the decay. ^{2}He, ^{5}Li, and ^{8}Be are destroyed by decay immediately after they are formed and can therefore, on average, only exist in extremely small quantities. The densities and the amount of time available for nuclear reactions in the big bang are not sufficient to initiate any further reactions on these small amounts of ^{2}He, ^{5}Li, and ^{8}Be. If the mass of the ^{8}Be nucleus would be smaller by just about a 1/1000 of a percent, the decay into two helium nuclei could not occur anymore and ^{8}Be would be stable. In this case, heavy elements could have been produced easily during the big bang, with drastic consequences for the existence of stars, including the sun, which uses the fusion of hydrogen from the big bang into heavier elements as its main energy source.



▲ **Fig. 1:** The relative abundance of the isotopes of the chemical elements in the solar system [1] as a function of their mass number (the total number of protons and neutrons in the nucleus). Some of the abundance peaks are marked with the mass number and the element that dominates the composition at this point.

Another striking feature in Fig. 1 is the relatively large abundance of nuclei around iron and nickel. This can again be explained by looking at the nuclear masses. The difference between the actual nuclear mass and the total mass of the nucleons (Z protons and N neutrons) determines through $E = mc^2$ the binding energy of the protons and neutrons in the nucleus. As an example, in ^{4}He this binding energy amounts to about 1% of the total mass. It turns out, that the nuclei around iron and nickel have the largest binding energies per nucleon of all stable nuclei. For example, a nucleon in ^{56}Fe is bound on average by 8.79 MeV = $1.41 \cdot 10^{-12}$ J [2]. Because of this, neither the fusion of two iron nuclei nor fission of an iron nucleus into smaller constituents releases energy - in fact one would need to provide energy to make these processes happen. As a consequence, the chain of nuclear fusion reactions in the interior of stars that produces energy by converting nuclei with less binding energy into nuclei with more binding energy per nucleon ends at iron and nickel. Earlier generations of stars have already begun to burn a small part of the hydrogen and helium from the big bang into iron and nickel. Supernova explosions have distributed these nuclei in the Galaxy, hence the relatively large abundance of these nuclei in the solar system.

The origin of the elements beyond iron and nickel, which are not produced by fusion reactions in stars, is still not fully understood. Nevertheless, we do find elements such as iodine, gold, or uranium in nature, so they have to be made somehow. We believe that the vast majority of these elements has been produced by neutron capture processes: a seed nucleus captures a number of neutrons until a radioactive isotope of the same element is formed. When this radioactive isotope decays by beta decay a new, heavier element is created. Successive neutron captures and beta decays can build heavier and heavier elements. Such neutron capture processes tend to form particularly large abundances of nuclei with closed neutron shell configurations, that occur at the "magic" neutron numbers N = 82 and 126. Similar to the closed electron shells of noble gases in atomic physics, the additional capture of a neutron on nuclei with such magic neutron numbers is hindered by the reduced energy gain. This is a direct consequence of the tiny change in nuclear mass by about 1:100,000 due to the closed neutron shell configuration. The result is a slowdown of the neutron capture process at this point that leads to the build up of particularly large amounts of nuclei. The corresponding peaks in the solar abundance distribution can be found in Fig. 1 at the mass numbers 130, 138, 195, and 208. So again it is the nuclear masses and the resulting neutron binding energies that point to the origin of heavy elements by neutron capture. As

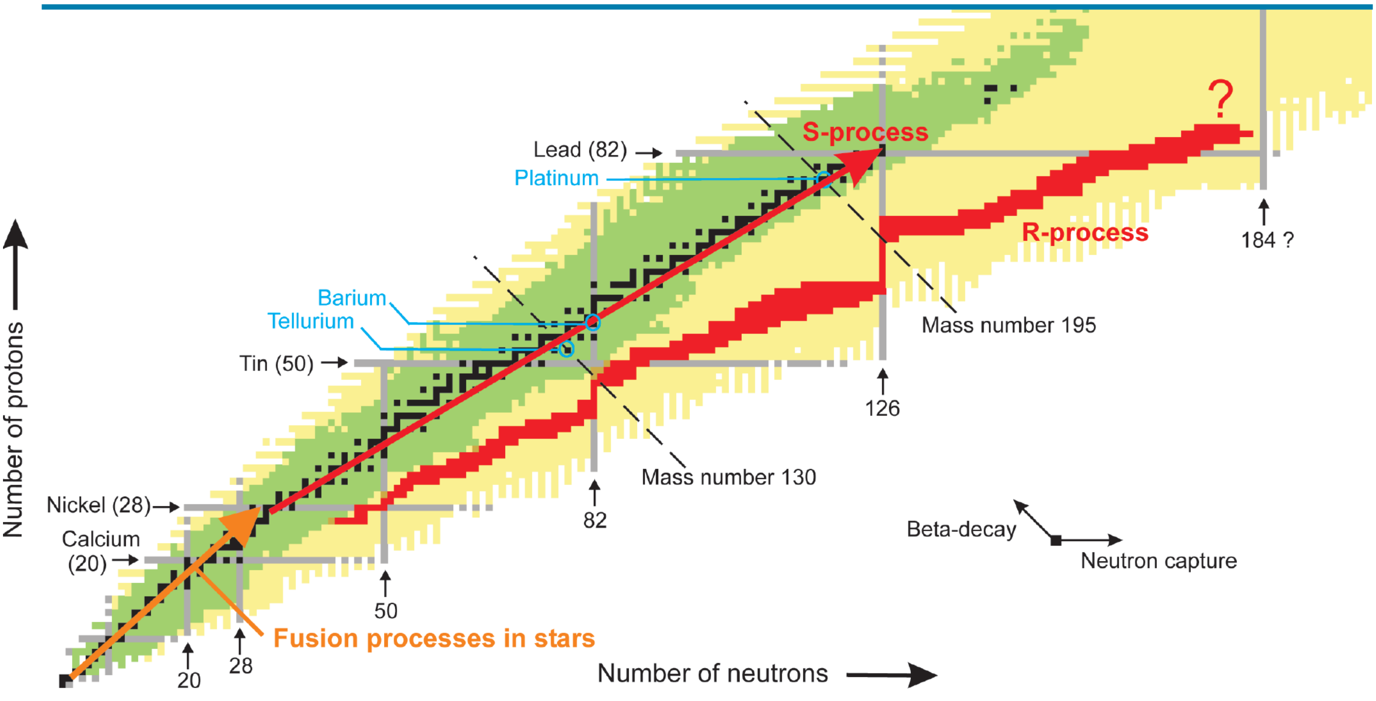
Fig. 1 shows, the abundance maxima occur pair wise. From this one can conclude that heavy elements are formed by two different neutron capture processes - a slow process (s-process) and a rapid process (r-process). The s- and the r- processes cross the closed neutron shells at different elements, so that one obtains two distinct abundance maxima at different mass numbers for each neutron shell closure.

The s-process

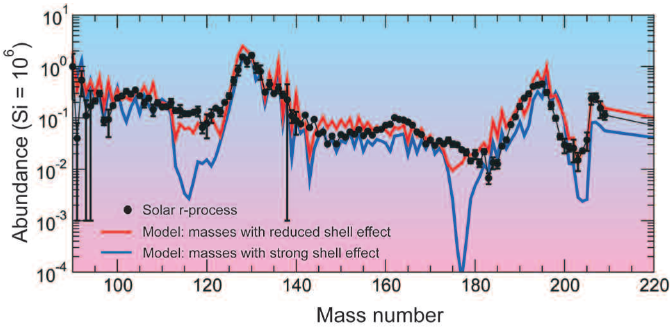
During the s-process neutron captures are in most cases much slower than beta decays. Radioactive isotopes formed after a neutron capture decay quickly into stable nuclei before the next neutron is captured. The s-process proceeds therefore along the so called valley of stability (Fig. 2) and crosses the $N = 82$ and $N = 126$ neutron shells at stable nuclei with mass numbers $A = 138$ (barium) and $A = 208$ (lead). The abundance maxima created by the s-process at these locations can be readily identified in Fig. 1. From the observation of technetium, which is an element without a stable isotope, on the surface of red giant stars the ongoing operation of the s-process has been demonstrated and the astrophysical site has been identified unambiguously. Because the masses and other properties of the nuclei participating in the s-process are known rather well one can calculate s-process abundances in stellar models quite reliably. Exceptions are the relatively uncertain neutron capture rates of some isotopes, especially in the beginning of the s-process. The experimental determination of precise neutron capture rates for the s-process is an important topic of current research in nuclear astrophysics [4]. Measurements of neutron capture rates on longer lived radioactive isotopes that can do both, capture neutrons and beta decay, so called s-process branching points, represent a particular challenge for future experiments. Important open questions also include the processes in red giants that produce the neutrons needed for the s-process. Poorly understood mixing processes in the stellar interior are particularly relevant, but uncertainties in the neutron producing nuclear reactions are a problem as well [5].

The r-process

The r-process is responsible for the origin of about half of the heavy elements beyond iron. Elements such as europium, gold, platinum, or uranium are mainly produced in the r-process [6, 7]. From the location of the abundance maxima in Fig. 1 at $A = 130$ (tellurium) and $A = 195$ (platinum) one can conclude that the r-process crosses the $N = 82$ and $N = 126$ neutron shells at nuclei with a mass number around $A = 130$ and $A = 195$ (see Fig. 2). These nuclei are extremely unstable. ^{130}Cd ($A = 130$, $N = 82$) is a cadmium isotope with a lifetime of only 162 milliseconds, and 195Tm ($A = 195$, $N = 126$) is an exotic thulium isotope which has never been observed in a laboratory. Obviously the neutron densities during the r-process are so large that neutron captures are much faster than beta decays so that extremely beta unstable nuclei can be formed. After their creation in the r-process these nuclei are converted into stable nuclei through a long chain of beta decays. In some cases these beta decays can emit neutrons, so the mass number of the final stable nucleus tends to be slightly lower than the mass number of the nucleus formed originally in the r-process, an effect which we neglected in our simple argument above.



▲ **Fig. 2:** Typical predicted path [3] of the r-process (in red) on the chart of nuclides. On this chart, the number of neutrons increases column wise to the right, while the number of protons (element number) increases row wise upward. Each box therefore represents a nucleus with a specific number of protons and neutrons. Nuclei within a horizontal row represent the different isotopes of a given chemical element. Marked in grey are the "magic" proton and neutron numbers, for which the respective shells are closed. Shown are nuclei, which are stable or so long lived that they naturally exist (black), unstable nuclei for which the mass is known (green) and all other unstable nuclei that are predicted by nuclear theory to exist (yellow). The diagonal dashed lines mark the mass numbers where the r-process abundance maxima occur (see Fig. 1). Also shown in a very schematic way is the path of the fusion processes in stars (orange arrow) and the s-process (red arrow). For neutron capture *N* increases by one, while for a beta decay *Z* is increased by 1 and *N* is decreased by 1 (see arrows).



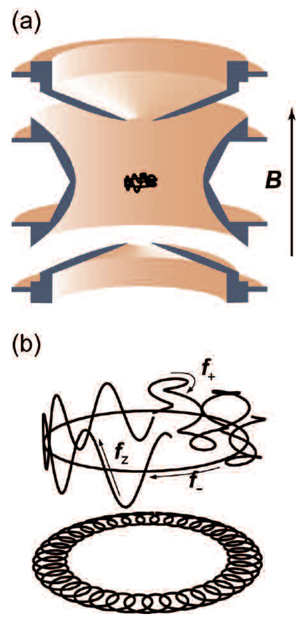
▲ **Fig. 3:** Contribution of the r-process to the isotopic abundances of the chemical elements in the solar system as a function of the mass number ("solar r-process"). This distribution is obtained by subtracting calculated contributions from the s-process and other, less important, processes from the observed solar abundance distribution shown in Fig. 1. The abundances are given in usual units relative to one million silicon nuclei. In addition we show the calculated abundances produced in two r-process models that only differ in the theoretical model used to predict the nuclear masses. One mass model shows pronounced shell closures, while the other has a reduced shell closure effect that might occur for very neutron rich nuclei (Data from K.-L. Kratz and B. Pfeiffer, University of Mainz, Germany [7]). This illustrates nicely the strong dependence of predicted r-process abundances on the nuclear masses.

To understand the r-process is one of the greatest challenges of modern nuclear astrophysics. So far it is not known with certainty where in the universe this process can occur. The difficulty for astrophysicists is to find ways to produce the required extreme neutron densities. One possibility is the neutrino flux that drives a wind of material off a hot neutron star forming in the core of a supernova explosion. Though it has been shown that an r-process can occur in such a neutron rich environment, it is still unclear how one can obtain the highest neutron densities needed to produce the heaviest r-process nuclei [8, 9]. Another possibility is the merging of two neutron stars into a black hole in a neutron star binary system. Model calculations have shown that very neutron rich material can be ejected in such an environment, but simulations also showed that such neutron star mergers might not be frequent enough to explain the observed abundances of heavy elements. Other suggestions for the r-process site include jets in supernova explosions, or gamma-ray bursts from collapsars created by the collapse of a very massive star into a black hole.

New astronomical observations over the last decade have led to dramatic progress in our understanding of the r-process [10]. Of particular importance is the discovery of a few stars in the halo of our Galaxy that are, compared to the sun, extremely iron poor, but strongly enriched in r-process elements. It is believed that these stars are so old that at the time of their formation the composition of the Galaxy was generally iron poor (iron is produced over time by supernova activity) and still extremely inhomogeneous. The r-process element enriched stars apparently formed from interstellar gas that was polluted by a nearby r-process event. In contrast to the solar abundances shown in Fig. 1, which are the product of probably hundreds of different nucleosynthesis events mixed together, the elemental abundances that one can measure through the detection of absorption lines in the photospheres of these stars allow one to determine the products of perhaps a single r-process event. From the few stars found so far one finds for a number of elements good agreement from star to star and also with the r-process contribution to the solar system, though there are interesting discrepancies that might point to the existence of multiple r-processes. In the coming years the discovery of maybe hundreds of such r-process enriched iron poor stars is expected from large scale astronomical survey programs such as HERES (Hamburg/ESO R-process Enhanced Star Survey) or SEGUE (Sloan Extension for Galactic Understanding and Exploration), part of a follow-up program to the Sloan Digital Sky Survey. The results are expected to lead to a new understanding of how neutron capture processes such as the r-process have enriched our Galaxy step by step with heavy elements.

Similar progress is now needed in nuclear physics. Without knowledge of the nuclear physics in the r-process, predictions from theoretical r-process models cannot be compared to observations in a meaningful and quantitative way. The understanding of the r-process is hampered by the fact that hardly any of the extremely unstable participating nuclei could be produced and studied at accelerator laboratories. Nuclear masses play an especially important role for the understanding of the r-process [7]. Most modern r-process models predict that the r-process occurs at high temperatures of a billion degrees or more. At such high temperatures energetic photons can excite nuclei so that they emit neutrons. Such photodisintegration reactions can counteract the rapid neutron captures. At which nucleus this happens within an isotopic chain depends mainly on the binding energy of the neutrons in the nuclei and therefore on the nuclear masses. At the nucleus where photodisintegration wins over neutron capture, the so called r-process waiting point, the r-process will temporarily stop and wait for the beta decay into the next isotopic chain, where the balance of neutron capture and photodisintegration is played out anew. For a given neutron density and temperature nuclear masses must be known in some cases to an accuracy of better than one part in one million to determine the waiting point nuclei. Nuclear masses therefore largely determine the path of the r-process on the chart of nuclides. Together with the beta decay half-lives of the waiting point nuclei, the masses determine also the speed of the process and the final abundance pattern. Precise nuclear masses are therefore essential to compare theoretical abundance patterns with observations. Without reliable nuclear physics the high precision observational data obtained with sophisticated telescopes cannot be quantitatively interpreted.

Unfortunately, most of the extremely neutron rich nuclei in the r-process are still beyond the reach of nuclear physics accelerator facilities. Exceptions



►**Fig. 4:** a) Sketch of a hyperbolic Penning trap (diameter about 2 cm). The motion of charged particles inside the trap is a superposition of three independent eigenmotions: a harmonic oscillation in the axial direction and in radial direction the magnetron and modified cyclotron motion.
b) Total ion motion and projection onto the *x*–*y*-plane. The motional amplitudes of the ions are less than 1 mm.

have been pioneering half-life measurements for a few dozen r-process nuclei. Such half-life measurements can now be performed with the smallest beam intensities of only a few ions per day [7, 11]. For the masses of r-process nuclei, on the other hand, one still has to rely on the theoretical predictions of nuclear mass models [12]. These calculations are by far not accurate enough - different models predict masses that differ by as much as 1:10,000, about a factor of 100 more than the accuracy needed for r-process calculations. In addition, fundamental changes in the structure of extremely neutron rich nuclei, which are poorly understood because of the lack of experimental data, could lead to even larger systematic errors in mass models. As an example, Fig. 3 shows the predicted abundances from r-process calculations obtained by using two different mass models. One model assumes that the size of the shell gaps and therefore the magnitude of the mass differences associated with closed neutron shells are reduced for extremely neutron rich nuclei. Such a reduction of shell effects is indeed predicted by some nuclear structure models. With such a modified mass model one does obtain a better agreement with observations [13]. However, as long as these possible systematic changes in masses are not confirmed experimentally one cannot decide which calculation uses the correct masses and whether instead fundamental problems in the astrophysical r-process model are to blame for the discrepancies. Less precise methods such as the determination of the electron energy spectrum from beta decay have provided recently a first hint for changes in the shell structure near $N = 82$ [14]. However, direct precision mass measurements of extremely neutron rich nuclides are of critical importance. The two most important methods in that respect will be presented in the following sections.

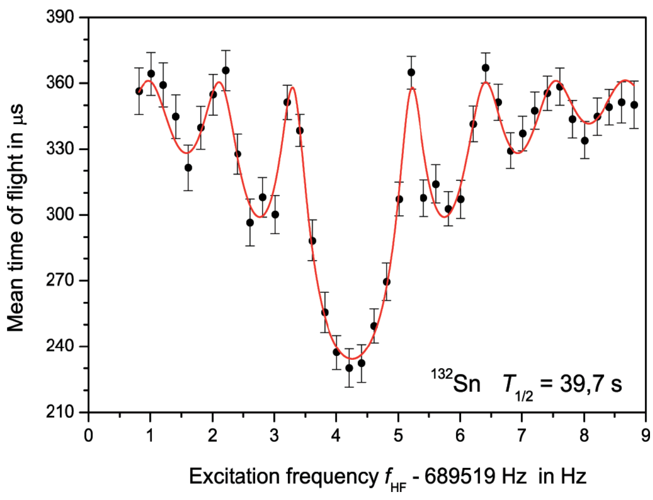
Precision mass measurements far from stability

Beams of extremely unstable neutron-rich nuclei can already be produced at current accelerators like ISOLDE at CERN in Geneva, Switzerland, at the heavy ion research institute (GSI) in Darmstadt, Germany, or at the NSCL facility at Michigan State University, USA [15]. To this end, a target is bombarded with accelerated stable nuclides. This leads to the production of exotic nuclides by fission or fragmentation, which are then available as ion beams for mass measurements. The challenge is to start the production process with as intensive stable beams as possible, to ionize and transport the exotic nuclei with little losses to the experiment, and to develop highly efficient experimental systems that can perform the measurements with very low beam intensities. The most modern techniques that have been developed at the facilities mentioned above made it already possible to produce nuclides close to or in some cases even in the r-process path with barely sufficient intensities for mass measurements.

The precision of mass determination necessary for r-process calculations, is routinely achieved by Penning trap mass spectrometers [15] like ISOLTRAP at ISOLDE/CERN [16] or LEBIT at the Michigan State University [17]. However, these devices only allow to access nuclides with lifetimes of several 10 milliseconds. The masses of short-lived nuclides with lower lifetimes far from stability can only be determined by the time-of-flight method, as *e.g.* in the experimental storage ring ESR at GSI at Darmstadt [18].

The Penning-trap mass spectrometer

The Lorentz force of a magnetic field confines the ions inside the Penning trap on a specific orbit. Since there is no force in the direction of the magnetic field lines, i.e. in the axial direction, a three-dimensional confinement is obtained by a superposition of the magnetic field with a weak static electric quadrupole potential.



▲ **Fig. 5:** Time-of-flight cyclotron resonance curve of the short-lived radionuclide ^{132}Sn with a half-life of 39.7s. The solid line is a fit of the theoretically expected line shape to the data.

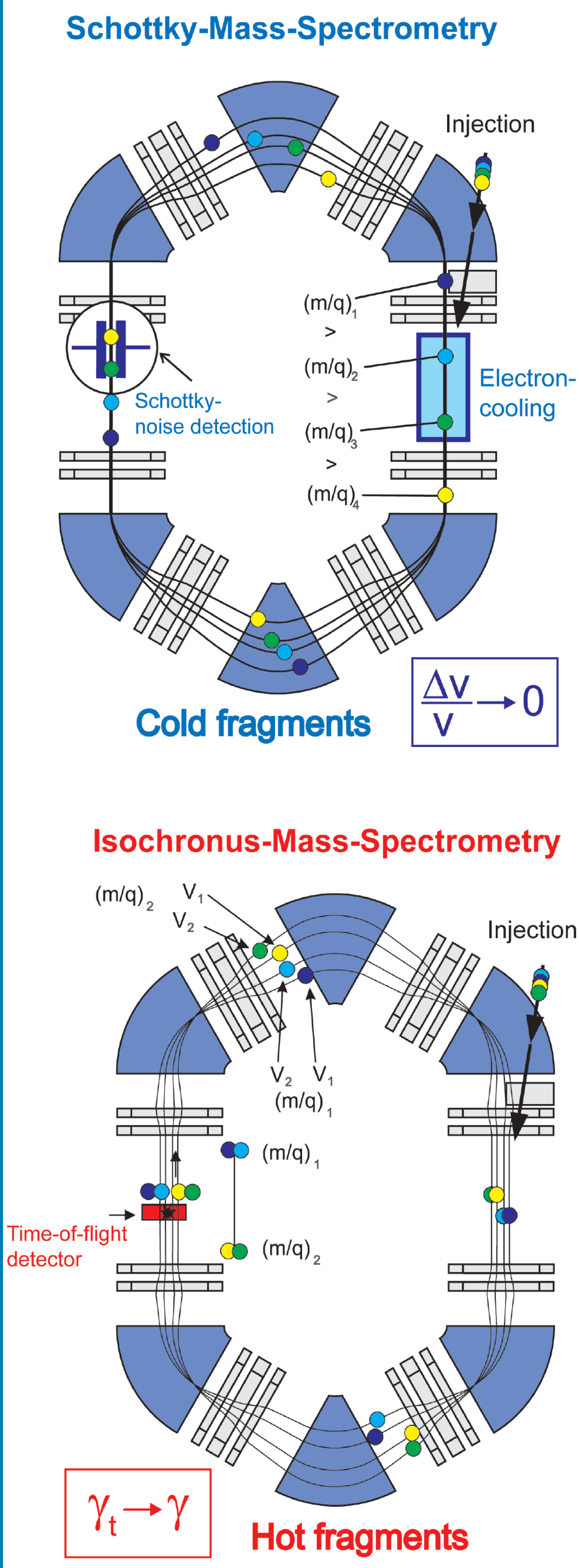
The geometry of a precision Penning trap can be realized by electrodes of hyperbolic shapes, where the surfaces are identical to the equipotential surfaces of the quadrupole potential (Fig. 4a).

The equations of motion for an ion in the resulting potential describe a trajectory consisting of the three independent harmonic oscillations as shown in Fig. 4b: the magnetron (f_-), the modified cyclotron (f_+) (both radial) and the axial frequency (f_z) [15]. Note, the sum of the frequencies of the two radial motions, $f_- + f_+ = f_c$, is equal to the cyclotron frequency and consequently equal to the revolution frequency of an ion with charge q and mass m in a pure magnetic field B:

$$f_c = \frac{1}{2\pi} \cdot \frac{qB}{m} \qquad (1)$$

The cyclotron frequency can be determined by the so called "time-of-flight cyclotron resonance method". Here, the motion of the stored ions inside the Penning trap is first excited by a radiofrequency f_{HF} close to f_c and subsequently the ions are ejected towards a detector. In case of a resonant excitation the radial energy of the ion increases, resulting in a reduced time of flight to the detector. The reason is that while passing through the strong magnetic field gradient the radial energy of the ion is converted into axial energy. The maximum energy gain and thus the shortest time of flight results for $f_{HF} = f_c$. Therefore, when measuring the time of flight as a function of the excitation frequency one finds a characteristic resonance (Fig. 5). The centre frequency of the resonance determines the cyclotron frequency and thus according to Eq. (1) the mass of the ion of interest, provided the magnetic field strength is known. To this end, before and after the actual measurement the procedure is also performed with a suitable ion with well-known mass for calibration.

The worldwide best Penning trap mass spectrometers allow one to measure the masses of radionuclides with production rates of only 100 ions per second, with half-lives as short as a few 10 ms and with an uncertainty as low as 10^{-8} [15]. Recently, several nuclides that are relevant for the r-process could be measured with high accuracy at ISOLTRAP. These include masses around the shell closures $N = 50$ (*e.g.*. ^{80}Zn and ^{81}Zn) and $N = 82$ (e. g. ^{132}Sn and ^{133}Sn), where one takes advantage of the fact that the r-process gets closer to the stable nuclei (see Fig. 2) [19].



The experimental storage ring

A second, very efficient method for mass measurements on radionuclides is mass spectrometry in a storage ring (Fig. 6). In this case, electric and magnetic fields are used for the three-dimensional storage of the ions and masses are determined from the revolution frequency in the ring. The relation between revolution frequency f, mass-to-charge ratio m/q and velocity v of different circulating ions in a storage ring is given by:

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1 - \frac{\gamma^2}{\gamma_t^2}\right) \qquad (2)$$

The quantity γ is the Lorentz factor of the ions and γ_t is an ion-optical parameter of the storage ring. For an unambiguous relation between revolution frequency and mass, the second (velocity dependent) term on the right-hand side of Eq. (2) must be cancelled. Two complementary methods apply to achieve this. In case of the so called Schottky mass spectrometry method (Fig. 6) electron cooling is applied so that $\Delta v/v \rightarrow 0$ [20]. The revolution frequency is measured by a Schottky noise analysis, i.e. at each turn the induced mirror charges of the circulating ions on two electrostatic pick-up electrodes are monitored and amplified. The Fourier transformed signal delivers the frequency and thus the mass spectrum (Fig. 7). The simultaneous storage of known masses for the calibration of the spectrum and unknown masses allows to measure up to several hundred nuclides with an uncertainty of a few 10^{-7} in a single experiment. Because the electron cooling takes time, this method can only be applied for nuclides with half-lives of the order of seconds or more. To overcome this limitation, the somewhat less precise method (uncertainties of about 10^{-6}) of isochronous mass spectrometry has been used successfully. In this case the storage ring is operated in an isochronous mode where $\gamma = \gamma_t$ [21] such that the orbit frequency of stored ions with the same mass-to-charge ratio is independent of their velocity and the right-hand term in Eq. (2) vanishes. This technique enables a mass determination of radionuclides with lifetimes as low as a millisecond or even less. For the detection of the circulating ions a foil is mounted in the ring aperture and the secondary electrons that are produced at any passage of an ion through the foil are detected. The ions circulate typically a few hundred to a few thousand times in the storage ring with a revolution time of about 0.5 microseconds.

Summary and outlook

Precision measurements of nuclear masses are of importance for the understanding of nuclear processes in stars and supernova explosions and the origin of the chemical elements in nature. Altogether, the masses of about 1000 short-lived radionuclides have been measured so far using Penning trap and storage ring mass spectrometry [2, 15]. This huge progress in nuclear physics, which already had impact on astrophysical models, not only required advances in measurement techniques, but also in the production of the exotic unstable nuclei at powerful radioactive ion beam facilities. At ISOLDE at CERN in Geneva extremely

◄ **Fig. 6:** Schematic view of the principle of the Schottky and isochronous storage ring measurement method. The circumference of the storage ring is about 110 m. For Schottky mass spectrometry all ions are cooled down to the same mean velocity by electron cooling. Because of their different mass-to-charge ratio (*m/q*), the ions perform trajectories with different lengths. In the case of isochronous mass spectrometry no cooling is involved and the ions have different velocities.

neutron-rich and short-lived tin isotopes close to the r-process path have already been produced and the masses have been measured with unprecedented accuracy in a Penning trap. At GSI in Darmstadt a few nuclides in the r-process path have been produced recently and have been measured using the storage ring method. Meanwhile, a novel method has been developed at the National Superconducting Cyclotron Laboratory at Michigan State University. Exotic nuclides are produced by fragmentation of a heavy nucleus, which is accelerated up to about 30% of the speed of light. After deceleration in a gas cell the exotic nuclides are injected into a Penning trap. With this method several nuclides in the r-process are within reach for precise mass measurements in the near future. In spite of this enormous progress the majority of nuclides that are important for the stellar nucleosynthesis cannot be produced and measured by means of the current facilities. For that reason new research facilities with unprecedented rare isotope production capabilities are planned or under construction, e.g. SPIRAL2 at GANIL, France, FAIR at GSI in Darmstadt, Germany or a new advanced rare isotope accelerator in the US. This new generation of facilities is intended to produce the majority of the nuclides participating in the astrophysical r-process with production rates sufficient for lifetime and mass measurements. Together with the expected progress in astronomy, detailed experimental tests of r-process models will be possible over the next decade and will provide new insights into the origin of the heavy elements in nature. ■

About the authors

Hendrik Schatz studied Physics in Karlsruhe and received his Ph.D at Heidelberg. After postdoctoral positions at UC Berkeley and GSI, Darmstadt he joined the faculty at Michigan State University and the National Superconducting Cyclotron Laboratory. He is now full professor and co-founder of the Joint Institute for Nuclear Astrophysics.

Klaus Blaum studied Physics in Mainz and received his Ph.D from there. After a postdoctoral position at GSI, Darmstadt, he went to CERN to lead the ISOLTRAP experiment. Since 2004 he is group leader of a Helmholtz-Research-Group at the University of Mainz. He has already received many awards, among them the Gustav-Hertz-Prize 2004 of the German Physical Society (DPG) and the Mattauch-Herzog-Prize 2005 of the German Society for Mass Spectrometry (DGMS).

References

[1] E. Anders und N. Grevesse, *Geochim. Cosmochim. Acta* **53**, 197 (1989)

[2] G. Audi, A. H. Wapstra, and C. Thibault, *Nucl. Phys. A* **729**, 3 (2003)

[3] H. Schatz *et al.*, *Ap. J.* **579**, 626 (2002)

[4] F. Kaeppeler, *Nucl. Phys. A* **752**, 500c (2005)

[5] F. Kaeppeler, *Prog. Part. Nucl. Phys.* **43**, 419 (1999)

[6] J. J. Cowan, F.-K. Thielemann, and J.W. Truran, *Phys. Rep.* **208**, 267 (1991)

[7] B. Pfeiffer, K.-L. Kratz, F.-K. Thielemann, and W. B. Walters, *Nucl. Phys. A* **693**, 282 (2001)

[8] S.E. Woosley and R.D. Hoffman, *Ap. J.* **395**, 202 (1992).

[9] K. Takahashi, J. Witti, and H.-Th. Janka, *A&A* **286**, 857 (1994)

[10] J.W. Truran, J. J. Cowan, C. A. Pilachowski, and C. Sneden, *Publ. Astr. Soc. Pac.* **114**, 1293 (2002)

[11] P. Hosmer *et al.*, *Phys. Rev. Lett.* **94**, 2501 (2005)

[12] D. Lunney, J. M. Pearson, and C. Thibault, *Rev. Mod. Phys.* **75**, 1021 (2003)

[13] B. Chen *et al.*, *Phys. Lett. B* **355**, 37 (1995)

[14] I. Dillmann *et al.*, *Phys. Rev. Lett.* **91**, 2503 (2003)

[15] K. Blaum, *Phys. Rep.* **425**, 1 (2006)

[16] F. Herfurth *et al.*, *J. Phys. B* **36**, 931 (2003)

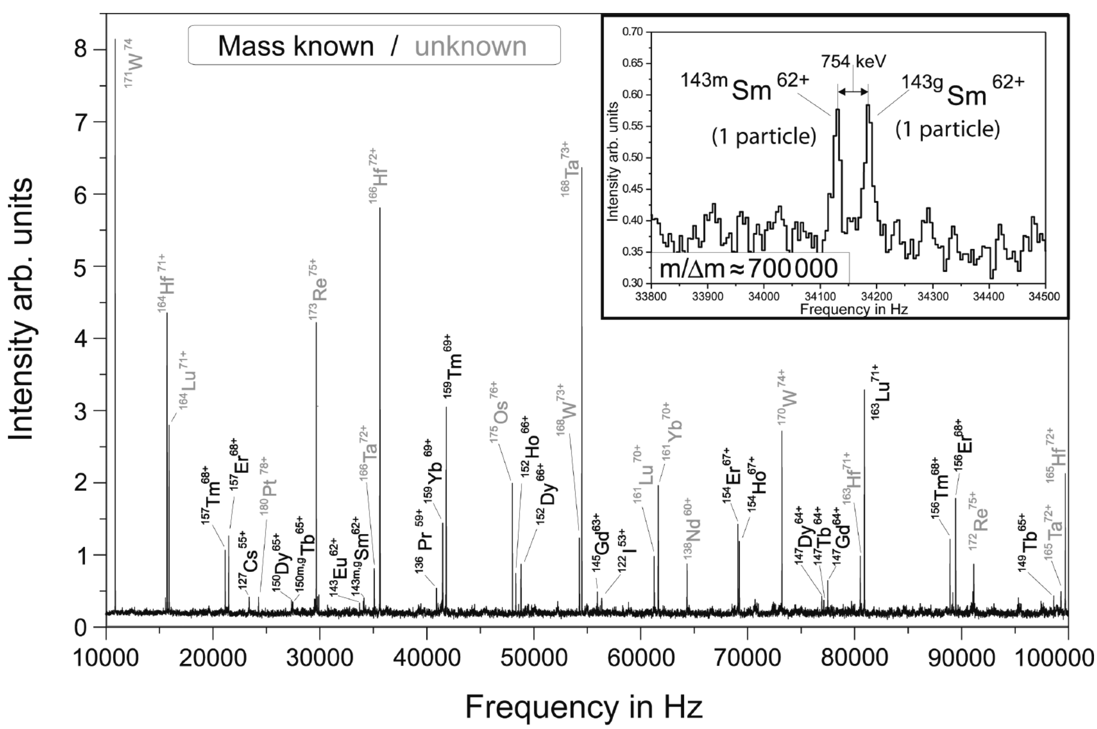
[17] G. Bollen *et al.*, *Nucl. Phys. A* **746**, 597c (2004)

[18] H.-J. Kluge, K. Blaum, and C. Scheidenberger, *Nucl. Instrum. Meth. A* **532**, 48 (2004)

[19] G. Sikler *et al.*, *Nucl. Phys. A* **763**, 45 (2005)

[20] T. Radon *et al.*, *Phys. Rev. Lett.* **78**, 4701 (1997); T. Radon *et al.*, *Nucl. Phys. A* **677**, 75 (2000)

[21] M. Hausmann *et al.*, *Nucl. Instr. Meth. A* **446**, 569 (2000)



◀ **Fig. 7:** Schottky spectrum of stored exotic nuclides, recorded in the storage ring. The frequency axis shows the difference of the 32th harmonics of the corresponding revolution frequencies of the ions ($\nu/c \approx 0.67$) with respect to the frequency of a stabilized local oscillator operating at about 59.33 MHz. The inset shows ground and isomeric state of fully stripped ^{143}Sm.

Is the Mexican wave really a ripple of excitation?

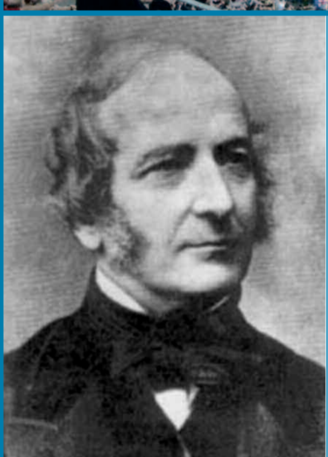
Julyan H. E. Cartwright,
Laboratorio de Estudios Cristalográficos, CSIC • E-18100 Granada • Spain.

The World Cup has come and gone once again, and with it we have seen more examples of that phenomenon of mass audience participation in stadia — first brought to the world's attention during the 1986 World Cup in Mexico — the Mexican Wave. In the pages of *Nature* at the time of the last World Cup in 2002 an analysis of the Wave appeared that suggested that it is an excitable phenomenon [1]. An excitable element is defined by its response to a perturbation: whereas a small disturbance causes merely an equally small response, a perturbation above a certain threshold in amplitude excites a quiescent element that then decays back to quiescence during a refractory period in which it is unresponsive to further excitation. Such elements, when coupled to their neighbours into an assembly, become an excitable medium. Forest fires, plankton populations, and the heart are just a few of the physical systems that can be thus described. Waves of excitation can propagate through excitable media; that is, like heart fibrillations, or forest fires, a wave sweeps through the medium and activates quiescent excitable elements, that then go through an unresponsive refractory period before becoming excitable once more.

People are certainly excited when they take part in the Wave, but are they excitable elements in the scientific sense of the term? To answer this question we may ask ourselves what would happen if two Mexican Waves were set off in opposite directions around a stadium — would they mutually annihilate on meeting, as excitable waves do? This is a crucial test, since one characteristic of an excitable medium is the refractory period during which excitation is impossible. In a forest, a second fire cannot pass until the vegetation burnt by the the first has grown back, and cardiac cells cannot fire again until they have recovered from their first firing. In other, nonexcitable, media lacking this refractory period, waves pass through each other rather than destroying each other. It's not obvious that there should be a refractory period involved in the Mexican Wave, or at least the limitation wouldn't seem to be physiological; there's no apparent reason why, having just sat down, wavers shouldn't jump back on their feet again for another wave coming from the other direction.

Nowadays, with the Internet, it is easier than it used to be to answer this type of question; masses of relevant data are just an Internet search away, and one often doesn't have to perform the experiment oneself — the results are already out there. And so it proved in this instance; the Wikipedia web page on the "audience wave" [2] contains the information sought for: "Simultaneous, counter-rotating waves have been produced", it informs us. The text goes on to note that one of these cases occurred at the Sydney Olympic Games in 2000, and also that "in non-circular seating arrangements, the wave can instead reflect back and forth through the audience". This is another reason to doubt that the Wave is excitable; unlike other waves, excitable waves do not reflect from boundaries.

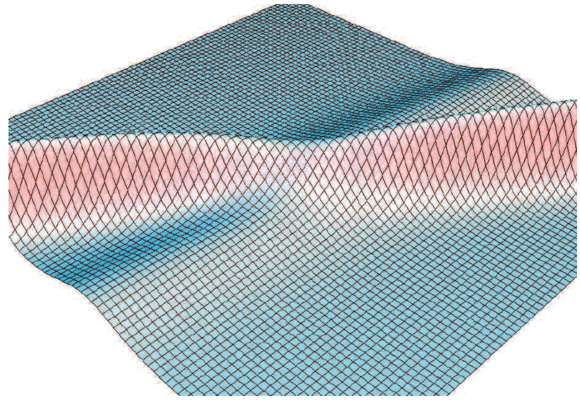
So what are Mexican waves if not excitable? Similar solitary waves like these that propagate without dispersing and pass through each other unscathed are found in many nonlinear media, and are often termed solitons. Nowadays solitons are used commercially in optical communications technology, but the archetypal examples are the shallow-water waves like that famously seen by their discoverer John Scott Russell on the Union canal near Edinburgh: "The mass of water ... rolled forward ... assuming the shape of a large solitary elevation. I followed it on horseback, and overtook it still rolling on at a rate of some eight or nine miles an hour ... [until] I lost it in the windings of the channel. Such, in the month of August 1834, was my first chance interview with that singular and beautiful phenomenon" [3]. From such beginnings in

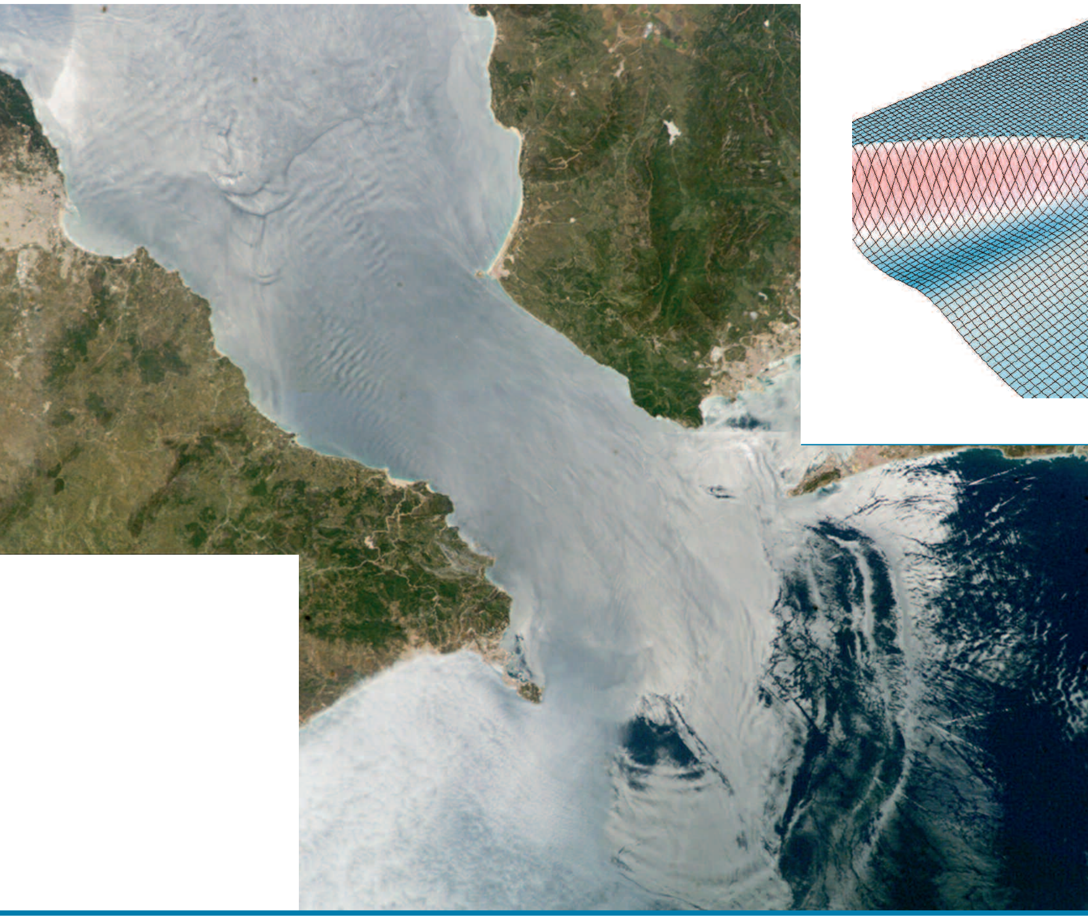


▲ **Fig. 1:** A Mexican Wave at the Confederations Cup, 2005 (image taken by Florian K. courtesy of Wikipedia under GNU Free Documentation licence)

► **Fig. 2:** Forest fires may be modelled as excitable systems; after this fire has extinguished itself, another cannot pass until the vegetation has regrown (image taken by John McColgan courtesy of Wikipedia)

◄ **Fig. 3:** John Scott Russell





▲ **Fig. 4:** Solitons in the Korteweg--de Vries equations describing shallow-water waves can pass through each other, emerge intact, and continue to propagate.

◀ **Fig. 5:** Solitons from internal waves in the Strait of Gibraltar (image courtesy of NASA Earth Observatory)

the nineteenth century, shallow-water solitons have latterly been implicated in less romantic phenomena such as large waves created by fast ships on shallow lakes and seas that can swamp small boats, and even larger waves, tsunami, for which the oceans themselves are shallow waters. Solitons exist in shallow water because it is a nonlinear medium — only a train of waves is stable in a linear medium, while a solitary wave disperses there because it is not stable — and similar solitons in the nonlinear medium of an optical fibre are exploited to transmit information over huge distances without loss. Mexican Waves then are better described as solitons rather than excitable waves.

The stadium crowd is a macroscopically discrete medium and not a continuum one such as water, but acts as a discretization of a nonlinear medium in which solitary waves can travel like in the shallow water of a canal. Of course, both solitons and excitable waves are the inevitable results of the dynamics of their underlying media, whether that is water, combustible vegetation, or cardiac tissue, while Mexican Waves are people having fun. People can choose whether or not to stand up and be part of a Wave, and Mexican Waves happen because most people present want to make a wave, rather than nothing at all, or something much more complicated; or rather than sitting back and watching the sport! So we shouldn't expect a set of strict rules to underlie Mexican Waves; rather heuristic principles. The underlying rule for being part of a Wave is like that we use at the beach, when we play the game of jumping through the incoming waves. It goes something like: "when a wave approaches me, get ready and jump up as it arrives".

As so often happens in science, from our initial examination of an apparently trivial phenomenon, the Mexican Wave, we can now begin to extract some worthwhile conclusions. On one hand, we are led to contemplate the ubiquity of wave phenomena in nonlinear media, both continuous and discrete; an excitable medium is just one instance of this, and is not the best description of the stadium crowd. On the other, we can start to see how complex human behaviour might be modelled through applying heuristic rules such as those we have described above. There is much to be learned through studying the new field of what has been called sociophysics with interacting agents that function by such rules [4]. It is fascinating to see how, both with Mexican Waves and in other cases, similar types of phenomena emerge from interacting intelligent agents as from the inaminate matter traditionally studied in other areas of physics. Scientifically then Mexican Waves may be described as solitons; we may say that they are exciting, but not excitable. ■

About the author:

Julyan Cartwright is with the Spanish Consejo Superior de Investigaciones Científicas (CSIC), and is based at the Laboratory for Crystallographic Studies in Granada, Spain. He may be contacted at julyan@lec.csic.es

References

[1] I. Farkas, D. Helbing, and T. Vicsek. Social behaviour: Mexican waves in an excitable medium. *Nature,* **419**:131–132, 2002.

[2] http://en.wikipedia.org/wiki/Audience wave.

[3] J. Scott Russell. Report on waves'. In *Proceedings of the 14th meeting of the BAAS,* pages 311–390, 1844.

[4] P. Ball. *Critical Mass: How One Thing Leads to Another.* Random House, 2004

Alexandru Proca (1897-1955)
and his equation of the massive vector boson field

Dorin N. Poenaru [1, 2] and Alexandru Calboreanu [1],
[1] National Institute of Physics and Nuclear Engineering • Bucharest-Magurele • Romania.
[2] Frankfurt Institute for Advanced Studies, J W Goethe University • Frankfurt am Main • Germany.
E-mail: Dorin.Poenaru@nipne.ro, calbo@ifin.nipne.ro

"*One of the most prodigious phenomenon of the recent history of physics was the extraordinary influence of Einstein's ideas not only on the contemporary scientific theory, but also on its applications*". These words have been written for the French hebdomadal *Le Figaro Litteraire* at the first jubilee in 1955 of one of the greatest landmarks of physics development – the *Annus Mirrabilis* 1905. The author, Alexandru Proca, at the time Directeur de Recherche at the CNRS France, was one of the great minds who entered physics at the right time. He belonged to the golden generation that shaped the structure not only of physics, but also of the science in its entirety. Proca devoted the most creative years of his life to the development of a sound relativistic quantum theory. During the effervescent years of the fourth decade of the 20th century, among scientists such as de Broglie, Schrödinger, Pauli, Heisenberg, Bohr and Dirac, Proca found an elegant and original path that remains even today actual and valid. It is an act of gratitude to revive his memory after another half century since he paid homage to the memory of Einstein just a few months before his own death.

Alexandru Proca was born in Bucharest in 1897 into a family of intellectuals. A brilliant school boy, mastering a few modern languages as well as Latin and some old Greek as was the curricula of any modern high school at that time, he showed an early appetite for mathematics. Soon after graduation, in the middle of World War I, he was mobilized (1917) and, after a brief instruction in a Military School, was sent to the front. 1918 was a triumphant year for his country, Romania, which saw most of its historic and ethnic borders settled. However the infrastructure for higher education, especially in the sciences and engineering, was quite weak and many young people used to go abroad, mainly to France and later to Germany, to acquire a proper training and qualification. Proca graduated from the newly inaugurated Polytechnic School (PS) in 1922 as an Electromechanical Engineer. He was employed by the Electrical Society Campina, a company at the centre of a rich oil field. At the same time he served as assistant professor at the chair of Electricity of the PS, which was headed by Professor Vasilescu Karpen a celebrity among many generations of engineers. The young Proca felt however that he was betraying his natural aptitude for the fundamental sciences, mathematics and physics. Already familiar with Einstein's papers he anticipated a major breakthrough and thought that he had something to say in this field. It is amazing that as early as 1920, still a student in engineering, he wrote a first paper on relativity, one of not many in the world at that time. So he left a promising and lucrative career to go to Paris (1923), full of expectations. Here, to his disappointment, he discovered that his diploma was useless. What he had to do was to matriculate from a French University and to pass the examinations for the 4-years curricula. This he did brilliantly and one year later he was *Licencié ès Sciences* at Sorbonne, Paris. In 1925 Marie Curie offered him his first job in her *Institut du Radium* where he was assigned to make measurements of β rays emitted by thorium descendants. He completed successfully the subject with a publication in Comptes Rendus (Nov. 1926), but that marked the end of his experimental investigations. Though he enjoyed much sympathy and appreciation from Mme Curie, she allowed him to pursue his natural calling towards theoretical physics that persisted during all these years in spite of his official daily duties. He was attracted by fundamental problems, such as the intimate nature of light quanta, the atomicity of entropy and even of time; he was one of the first thinkers about a discontinuous spatio-temporal frame.

◀ Alexandru Proca (1897-1955).

It was however de Broglie who directed him towards the mainstream of theoretical pursuits at that time, namely the Dirac equation and the quantum relativistic fields that had just started to take shape in the pioneering works of Born and Jordan, Dirac himself and Heisenberg. Proca engaged seriously in the programme and after a series of six papers devoted to the Dirac equation published in C. R Acad. Sci. Paris, (1930-33), and two more on the properties of the photon, he submitted an exceptional doctorate thesis to a commission: Jean Perrin, Louis de Broglie, Léon Brillouin and Aimé Cotton. In 1930 Proca received French citizenship and married Marie Manolesco with whom he had a son, George Proca [1-3].

From 1929, when *Les Annales de l'Institut Henri Poincaré* was founded, Proca was the editor of this famous journal. In 1934 he spent one year with E. Schrödinger in Berlin and a few months with N. Bohr in Copenhagen, where he met Heisenberg and Gamow. From 1936 to 1941 he developed his masterpiece work, the theory of massive vector (spin 1) boson fields governing the weak interaction and the motion of spin-1 mesons. Prestigious scientists such as Yukawa, Wentzel, Taketani, Sakata, Kemmer, Heitler, Fröhlich and Bhabha, reacted favourably to his equations in 1938. W. Pauli [4-6] mentioned Proca's theory in his Nobel lecture. As a particular sign of his world-wide recognition one can mention his invitation to attend in 1939 the *Solvay Congress*. To his misfortune, this Congress could not take place due to the outbreak of World War II.

During the war he was for a short time Chief Engineer of the French Radio broadcasting Company. In 1943 he moved to Portugal where he lectured at the University of Porto. In 1943-45 he was in the United Kingdom at the invitation of the Royal Society and the British Admiralty to join the war effort. After the war he started in 1946 the *Proca seminar* series in Paris with many prestigious invited speakers from France and abroad including A. Einstein, H. Yukawa and W. Pauli. This seminar contributed very much to the education of young French particle physicists. He accepted to organize with

P. Auger in 1950 the Theoretical Physics Colloquium of CNRS and in 1951 to be the French delegate at the General Meeting of the International Union of Physics. By that time the Proca equation was indeed famous as the only sound theoretical basis of the Yukawa meson. Starting in 1953 Proca began a fight with a laryngeal cancer that lasted until December 13, 1955 when he passed away. He left a major heritage in theoretical physics that by its actuality goes beyond historical interest.

Proca (massive vector boson) field

Proca extended the Maxwell equations to quantum field theory. For a massive vector boson (spin1) field the Proca equation

$$\Box A^{\nu} - \partial^{\nu}(\partial\mu A^{\mu}) + m^2 A^{\nu} = j^{\nu}$$

is obtained as a Euler-Lagrange equation emerging from the Lagrangian density

$$\mathcal{L} = -(1/4)\, F_{\mu\nu} F^{\mu\nu} + (1/2) m^2 A_{\mu} A^{\mu} - j_{\mu} A^{\mu}$$

after expressing the antisymmetric field-strength tensor,

$$F^{\mu\nu} = \partial^{\mu} A^{\nu} - \partial^{\nu} A^{\mu},$$

in terms of the four potential A^{μ}. One assumes the Einstein's convention: summing over repeated indices.

$$\Box = (\partial^2/\partial t^2) - \nabla^2$$

is the d'Alembertian operator while ∇^2 is the Laplacian. The 4-potential and current density are

$$A^{\mu} = (\varphi; \boldsymbol{A}), \quad j^{\mu} = (\rho; \boldsymbol{j})$$

Scalar j and vector $\boldsymbol{A}$ potentials are introduced via

$$E = -\nabla\varphi - \partial\boldsymbol{A}/\partial t, \quad \boldsymbol{B} = \nabla \times \boldsymbol{A}$$

In his Nobel lecture [4], W. Pauli noted: "The simplest cases of one-valued fields are the scalar field and a field consisting of a four-vector and an antisymmetric tensor like the potentials and field strengths in Maxwell's theory. While the scalar field is simply fulfilling the usual wave equation of the second order in which the term proportional to m^2 has to be included, the other field has to fulfill equations due to Proca which are generalization of Maxwell's equations."

After Yukawa's hypothesis of a particle mediating the nuclear interaction this particle was initially called the mesotron, or alternatively the Proca particle. Yukawa won the Nobel Prize in 1949 for his prediction (in 1934) of the existence of mesons on the basis of theoretical work on nuclear forces. By analogy with photons mediating the electromagnetic interaction he assumed the nuclear forces, acting between nucleons, are mediated by such bosons. As he suggested, the study of cosmic rays gave the first experimental evidence of the new particles. Yukawa employed a scalar field equation. He based his initial argument on the Klein Gordon scalar equation (zero spin) which not only was in conflict with relativity, but led to wrong quantitative results. It was Proca's equation that rendered Yukawa's genial intuition the theoretical ground suitable for a spin one particle.

Pauli [5] wrote: "This case holds the centre of current interest since Yukawa supposed the meson to have spin 1 in order to explain the spin dependence of the force between proton and neutron. The theory for this case has been given by Proca". Around 1970 there were many theories attempting to explain the nuclear interaction. Presently according to quantum chromodynamics, the strong interaction, mediated by massless gluons, affects only quarks and antiquarks; it binds quarks to form hadrons (including the proton and neutron).

Nonzero photon mass, the graviton and the superluminal radiation field.

The possibility and the effects of a non-zero photon rest mass is incorporated into the Proca equations. Implications of a massive photon are extraordinary: the variation of light velocity c; a longitudinal electromagnetic component of radiation and gravitational deflection; the possibility of charged black holes; the existence of magnetic monopoles; the modification of the standard model, etc. An upper limit for the photon rest mass [7] is $m_{\gamma} \leq 10^{-49}$ g. The hypothesis of a massive photon has consequences that might transcend the limits of physics itself. One such consequence is that the speed of the photon would depend on its frequency according to the theory of relativity. The speed of light will remain a simple universal constant. Other consequences refer to the violation of the Coulomb law, light propagation and the spatial extension of the electromagnetic field. These facts also provide a clue on how independent searches should be conducted, from laboratory bench tests of electrostatic screening to intergalactic effects. In one of the most spectacular experiments, undertaken by the Pioneer 10 spacecraft, the magnetic field decay around Jupiter [8] was measured.

One should point out that the m^2 term in the Proca equation is not a fancy idea of the author; its presence is in perfect agreement with the relativistic invariance of the electromagnetic field and the relativistic conservation of energy. It is the m=0 hypothesis, so much familiar to us, that comes as a supplementary condition and has to be checked.

The concept of a graviton of non-zero rest mass may be defined in two ways: phenomenologically, by a mass term in the linear Lagrangian density, as in Proca electrodynamics, and self-consistently, by solving Einstein's equations in the conformal flat case. The rest mass of the graviton was given in terms of the three fundamental constants: the gravitational, Planck, and the light velocity. The Einstein-Proca equations, describing a spin-1 massive vector field in general relativity, have been studied [9] in the static spherically-symmetric case. It has been shown that a special case of the gauge theory of gravity is effectively equivalent to the coupled Einstein-Proca theory. The Einstein-Proca field equations are frequently discussed in connections with dark matter gravitational interactions. At the level of string theories there are hints that non-Riemannian models, such as Einstein-Proca-Weyl theories may be used to account for the dark matter. Superluminal (faster than light) particles, *tachyons*, with an imaginary mass of the order of $m_e/238$, can be described by a real Proca field with a negative mass square [10]. They could be generated in storage rings, in the Jovian magnetosphere and in supernova remnants.

Proca's heritage is well established. Maxwell and Proca theories may be found in textbooks [11] as important examples of relativistically invariant formulation of the field equations for a free field. There are many publications referring to Proca directly in their title: the Einstein-Proca model (*e.g.* [9,13]), the Einstein-Proca-Weyl theories [12], or the Maxwell-Chern-Simons-Proca [14] electrodynamics. His physics opens new roads for theoretical and experimental investigations in the 21st century, proving once more that surprises are still in store. There were great moments of physics in the past as there will be in the future. ■

About the authors

Alexandru Calboreanu, president of the Romanian physical society, has received his PhD from the University of Oxford (1970). His main works are in studies of nuclear reactions and the stability of nuclei. He has taught at the University of Constanta, which has conferred on him the title of Doctor Honoris Causa.

Dorin N. Poenaru is Professor at the National Institute of Physics and Nuclear Engineering, Bucharest and is frequently invited to the Frankfurt Institute for Advanced Studies. He is mentioned in Encyclopaedia Britannica with A. Sandulescu and W. Greiner for predicting heavy particle radioactivity.
Both authors have fulfilled terms as scientific directors of their institute in Bucharest.

References

[1] G.A. Proca, Alexandre Proca. O*euvre Scientifique Publiée,* S.I.A.G., Rome, 1988.

[2] A. Calboreanu, *Rom. J. Phys.* **49** (2004) 3.

[3] http://www.th.physik.uni-frankfurt.de/~poenaru/PROCA/Proca.html (2005). D.N. Poenaru, *E-print, physics/0508195*, http://arXiv.org, 2005.

[4] W. Pauli, *Nobel lecture*, December 13, 1946.

[5] W. Pauli, *Rev. Mod. Phys.* **13** (1941) 213.

[6] C. P. Enz, *No time to be brief* (A scientific biography of Wolfgang Pauli), *Oxford University Press*, New York, 2004.

[7] L.-C. Tu, J. Luo, G.~T. Gillies, *Rep. Prog. Phys.* **68** (2005) 77.

[8] D. Levrett, A.S. Goldhaber, M.M. Nieto, *Phys. Rev. Lett.* **35** (1975) 1402. A.S. Goldhaber, M.M. Nieto, *Scientific American* **234** (1976) 86.

[9] C. Vuille, J. Ipser, J. Gallagher, "Einstein-Proca model, micro black holes, and naked singularities", *General Relativity and Gravitation*, 34 (2002) 689.

[10] R. Tomaschitz, *Physica A* **293** (2001) 247; *A* **335** (2004) 577; *Eur. Phys. J. D* **32** (2005) 241.

[11] W. Greiner, *Relativistic quantum mechanics*; W. Greiner and J. Reinhardt, *Field quantization*; W. Greiner and A. Schäfer, *Quantum chromodynamics*, Springer, Berlin, 2000, 1996, 1995, respectively.

[12] R. Scipioni, "Isomorphism between non-Riemannian gravity and Einstein-Proca-Weyl theories extended to a class of scalar gravity theories", *Class. Quantum Grav.,* **16** (1999) 2471.

[13] R. W. Tucker and C. Wang, C., "An Einstein-Proca-fluid model for dark matter gravitational interactions", *Nucl. Phys. B* - Proc. suppl., **57** (1997) 259.

[14] H. Belich, T. Costa-Soares, M. M. Ferreira Jr., J. A. Helay-Neto, "Classical solutions in a Lorentz violating scenario of Maxwell-Chern-Simons-Proca electrodynamics", *Eur. Phys. J. C* **42** (2005) 127.

Water from Heaven

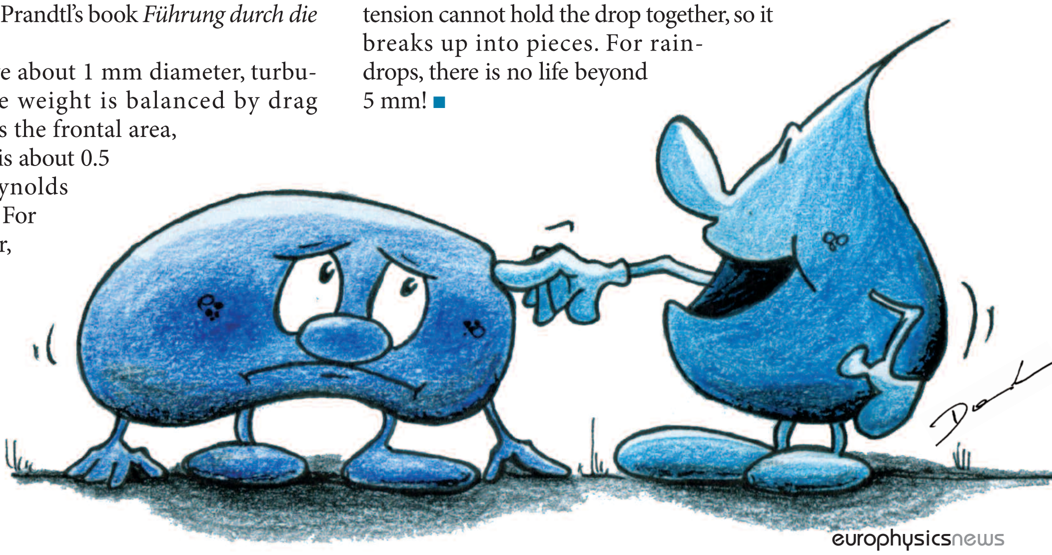
L.J.F. (Jo) Hermans,
Leiden University • The Netherlands • E-mail: Hermans@Physics.LeidenUniv.nl

Large rain drops fall faster than small ones, that much is obvious for any physicist. But let's be a bit more precise. The terminal velocity follows from the balance between the weight of the drop and its air resistance. What exactly is the resistance of a drop falling through the atmosphere? We have to distinguish two regimes here. If the droplets are very small, like cloud droplets (or fog particles, if you wish), the Reynolds number is so small that Stokes' formula applies: the air resistance is proportional to viscosity, radius and velocity: $F = 6\pi\eta Rv$. For a typical cloud droplet having a radius of 0.01 mm, we find a terminal velocity of about 1 cm/s. That is very small indeed. But it goes up rapidly with size: since its weight is proportional to R^3 and the resistance only to R, the terminal velocity increases with the square of the size for such droplets. That applies to droplets up to about 0.1 mm in diameter, according to the handbooks (good old Ludwig Prandtl's book *Führung durch die Strömungslehre*, for example).

For ordinary raindrops, above about 1 mm diameter, turbulent flow dominates. Here the weight is balanced by drag $F_D = C_D\pi R^2.1/2\rho v^2$, where πR^2 is the frontal area, C_D is the drag coefficient, which is about 0.5 for a sphere at the relevant Reynolds numbers, and ρ the density of air. For a rain drop of 1 mm in diameter, we find a terminal velocity of 16 km/h. Note that in this regime the velocity is proportional to the square root of the diameter. Consequently, a 3 mm raindrop reaches 28 km/h. And so on, we would guess. Given the above, we may expect that for the biggest drops - 5 mm, say - the terminal velocity is well above 35 km/h.

Wrong! Something interesting happens, as already noticed by the German physicist, Philipp Lenard, a century ago. Using a vertical wind tunnel to balance the speed of the drop, he noticed that drops larger than about 3 mm diameter become deformed to the shape of a small pancake, and have a flat bottom. Consequently, their frontal area is larger than for spherical droplets having the same mass. As a result of the increased drag, the terminal velocity hardly increases any further: for raindrops of 4 and 5 mm it reaches an asymptotic value of about 29 km/h, which is practically the same speed as that already reached by the 3 mm drops.

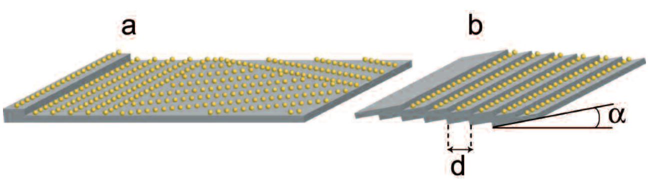
And beyond 5 mm? As soon as the diameter reaches about 5.5 mm, the forces become so large that surface tension cannot hold the drop together, so it breaks up into pieces. For raindrops, there is no life beyond 5 mm! ■



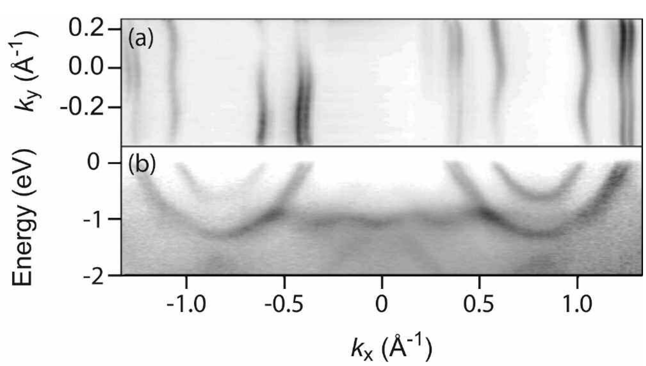
Density waves in atomic necklaces

Paul C. Snijders [1], Sven Rogge [1], and Hanno H. Weitering [2, 3]
[1] Kavli Institute of NanoScience, Delft University of Technology • 2628 CJ Delft • The Netherlands
[2] Department of Physics and Astronomy, The University of Tennessee • Knoxville, TN 37996 • USA.
[3] Materials Science and Technology Division, Oak Ridge National Laboratory • Oak Ridge, TN 37831 • USA.

One-dimensional (1D) systems have always captured the imagination of physicists. In the ultimate 1D limit, a crystal is nothing but a string of atoms, akin to a necklace of tiny pearls. Most physics graduates undoubtedly associate 1D systems with the simple models used in introductory level quantum mechanics or statistical mechanics courses. Indeed, 1D model systems represent pedagogical and often most useful illustrations of the basic physics principles that govern more realistic condensed matter systems. These principles tell us, for instance, that an ideal atomic chain with a single metallic band should be unstable with respect to a Peierls distortion. A Peierls distortion is a condensed state of the 1D electron gas whose formation is triggered by the strong coupling between electrons and quantized lattice vibrations (phonons). The upshot is that such a wire would not conduct electricity at low temperature. Alternatively, atom wires could display exotic many-body physics. It has been predicted that, due to strong electron-electron interactions in 1D, the concept of single electrons should even break down and that it is only meaningful to discuss their collective behavior (*i.e.*, excitations). Such a state of matter is referred to as the Luttinger-Tomonaga liquid.



▲ **Fig. 1:** (a) Schematic illustration of the threefold degeneracy of anisotropic reconstructions on the Si(111) surface. Note the limited "wire-length" due to the small domain sizes. (b) The array of step edges on a vicinal Si(111) surface produces a single domain atom-wire array. α and *d* are the miscut angle and the resulting atom wire spacing, respectively.



▲ **Fig. 2:** The Fermi surface (a) and band structure (b) of the Si(553)-Au surface as measured with ARPES: photoemission intensity (dark) as a function of energy and wave vector along the wires (a), and as a function of wave vector parallel and perpendicular to the wires (b). Reprinted figure (a) and (b) with permission from Ref. [8], copyright (2003) by the American Physical Society.

But even though the theory of ideal 1D systems has advanced much, experimental realization of truly 1D condensed matter systems remains a daunting task; it is impossible to suspend a long string of atoms in free space. Nonetheless, due to the progress in nanoscience, it is now possible to synthesize and tailor novel nanophase materials that mimic the ultimate 1D limit quite closely. As a result, crucial questions regarding the physics of atom wires can be experimentally addressed. For instance: would a string of atoms conduct if it is laid down on a substrate? How can the often detrimental effects of the inevitable structural imperfections or those of thermodynamic fluctuations be alleviated? Or perhaps the most fundamental and practical issue: would atom wires actually be thermodynamically stable?

Experimental approaches toward creating 1D systems are often classified as 'top down' or 'bottom up' fabrication. The top-down procedure refers to artificial (lithographic) creation of 1D nanostructures. A natural way to produce atom wires is a bottom-up method that employs the most common 1D *line*-defects on surfaces, namely atomic step-edges, as a template for self-assembly. Moreover, artificially created nanostructures are generally unstable, whereas self-assembled (nano-) structures instead can be thermodynamically stable, just because the driving force in their formation is not a kinetically enforced low-dimensional ordering, but purely a drive toward the lowest energy state [1,2].

We use the symmetry breaking properties of surfaces and the reconstructions of their topmost atom layers to realize self-assembled macroscopic arrays of atom wires. To this end, we have used vicinal (stepped) Si surfaces. Besides the thermodynamic stability inherent to self-assembly based fabrication, an extra advantage of this approach is that the spatial access to these atom wire arrays allows for a detailed investigation of electronic instabilities in these wires, even at a local scale. The atom wires can reach *macroscopic* lengths on vicinal surfaces; their length is only limited by occasional step edges crossing the wires. On the other hand, producing atom wires via this bottom-up method inevitably introduces (intrinsic) defects. This should not necessarily be viewed as a drawback, since it provides a much-needed opportunity to study the dramatic influence of imperfections in atom wires on their (in-)stabilities. Because they are located at surfaces, the wires can be studied conveniently using well-developed techniques such as Scanning Tunneling Microscopy and Spectroscopy (STM and STS), and Angle Resolved Photoemission Spectroscopy (ARPES).

Atom wires on stepped Si surfaces

The Si(111) surface displays a threefold symmetry. Consequently reconstructions with a lower symmetry will form in three degenerate domains of limited size on the surface, as illustrated in Figure 1(a) [3]. Upon adsorption of less than a monolayer of Au on a vicinal (stepped) surface, the additional anisotropy imposed by the step-edges drives the formation of a regular array of parallel 1D atom wires that can have macroscopic lengths, see Figure 1(b). Changing the miscut angle α between the surface plane and the (111) plane, permits a systematic study of the electronic properties as a function of inter-wire distance d [3]. Note that even though these atom wires are mechanically supported by a bulk Si substrate, their *electronic* structure is decoupled from that of the bulk Si substrate because the metallic states of the atom wires lie in the band gap of the Si substrate.

Electronic instabilities

Several studies on atom wire arrays on Si surfaces have been reported in the literature so far. In particular, photoemission measurements (probing the band structure of the surface region of a solid in *k*-space) on the Si(111)4 x 1-In and the Si(557)-Au atom wire reconstructions reveal metallic bands which appear to cross the Fermi level at room temperature [4,5]. However, STM images at low temperatures reveal a doubling of the periodicity of the atom wire structure and a gap in the band structure [4,6]. These effects have been interpreted as evidence for the occurrence of a charge density wave or Peierls distortion (for a review on charge density waves, see Ref. [7]). A charge density wave originates from the interaction between electrons and phonons. It is usually accompanied by a structural modulation: when the band filling of the undistorted (high-symmetry) phase is $1/n$, the lattice assumes an n-tupled superperiod below the transition temperature. This charge density wave is furthermore accompanied by a band-gap opening. The gap opening stabilizes the charge density wave state, in spite of the increase in lattice strain. Charge density waves are not necessarily commensurate (n does not need to be integer), but commensurate charge density waves are intuitively expected to be more stable than incommensurate charge density waves because the electronic system can more easily adapt to the periodic potential of the lattice. The gap opening possibly prevents the observation of low-energy (electron-) interaction effects close to the Fermi level at low temperatures. This means that the electrons in an atom wire may prefer to order in space, and in doing so the metallicity of the wires is destroyed.

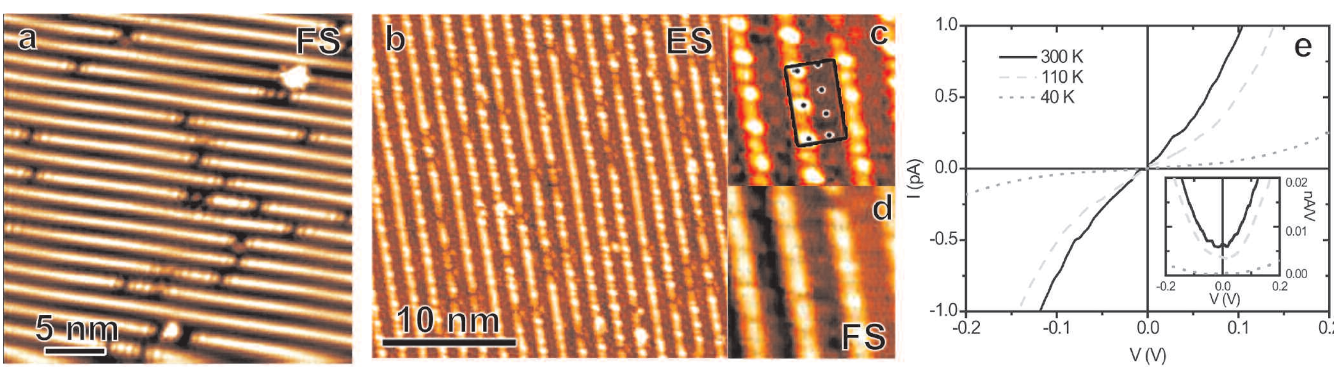
There might be a way to prevent charge density wave ordering and the associated destruction of the metallic state. In a multi-band 1D system, there could be a competition between different charge density wave states and it is conceivable that the condensation of one charge density wave and accompanying lattice distortion would alleviate or even eliminate electronic instabilities in the other bands, which would then retain their metallic character. Moreover, the Coulomb interaction that is present between charge density waves with different periodicities could also inhibit the condensation of (one of these) charge density waves.

In this respect, the atom wires present on vicinal Si(553)-Au surface show a promising electronic structure; room temperature photoemission measurements reveal three bands crossing the Fermi level, see Figure 2 [3,8]. The band fillings $1/n$ of the three bands are 0.27, 0.51, and 0.56 ± 0.01, respectively [3,8]. This system thus constitutes a multi-band system, where at least two of the three bands (the 0.27- and the 0.56-filled bands) are incommensurate.

Atom wires on Si(553)-Au

In this article we discuss recent experiments on atom wires on the vicinal Si(553) surface [9]. The atom wires were created by depositing a submonolayer amount of Au onto the Si(553) surface. A subsequent thermal anneal at 1120 K ensures that the surface has reached an ordered equilibrium structure consisting of atom wires. This surface preparation takes place in an ultra high vacuum (UHV, base pressure $< 5 \times 10^{-11}$ mbar) system, to protect the atom wires from ambient conditions.

Following the preparation of the atom wire arrays, the sample was transferred to the STM, which is located in the same UHV system. We have recorded STM images and STS *I-V* curves measured at room temperature and various low temperatures [9]. In an STM, an atomically sharp tip is brought in tunneling contact with the surface, and is subsequently scanned over the surface while maintaining a constant tunneling current using a feedback loop. Due to differences in height and in the local density of states of the surface, the absolute vertical tip-position will vary so as to maintain a constant tunneling current. By plotting the change in vertical tip-position as a function of x and y coordinates, an atomic-scale real space image of the surface structure is obtained. Note that this image contains information on both the atomic structure and the local density of states. In Figure 3(a) we present a filled state (electrons tunneling from the filled density of states of the sample to the tip) room temperature STM image of the Si(553)-Au surface. The image shows rather smooth atom wires that are cut by seemingly random vacancy-like defects. The empty state image (not shown) is very similar. The corresponding STS *I-V* curve is displayed in Figure 3(e). In an STS experiment we ramp the voltage between sample and tip and measure locally the tunnel current at a constant tip-sample distance. The room temperature *I-V* curve shows a finite slope at zero bias, indicating a finite density of states at the Fermi level, which is consistent with the metallic band structure measured by ARPES. However, after decreasing the



▲ **Fig. 3:** (a) Room temperature filled state (-0.5 V, 50 pA) STM image showing atom wires, locally cut by vacancy-like defects. (b) Empty state (1 V, 100 pA) STM image at 40 K and magnification (c). In (c) the tripled periodicity on the chains and doubled periodicity in between the chains are indicated. (d) Filled state (-1 V, 100 pA) STM image of the same area as (c). (e) STS *I-V* curves, measured at the indicated temperatures. The inset shows the numerical derivatives. Reprinted figures (a) to (e) with permission from Ref. [9], copyright (2006) by the American Physical Society.

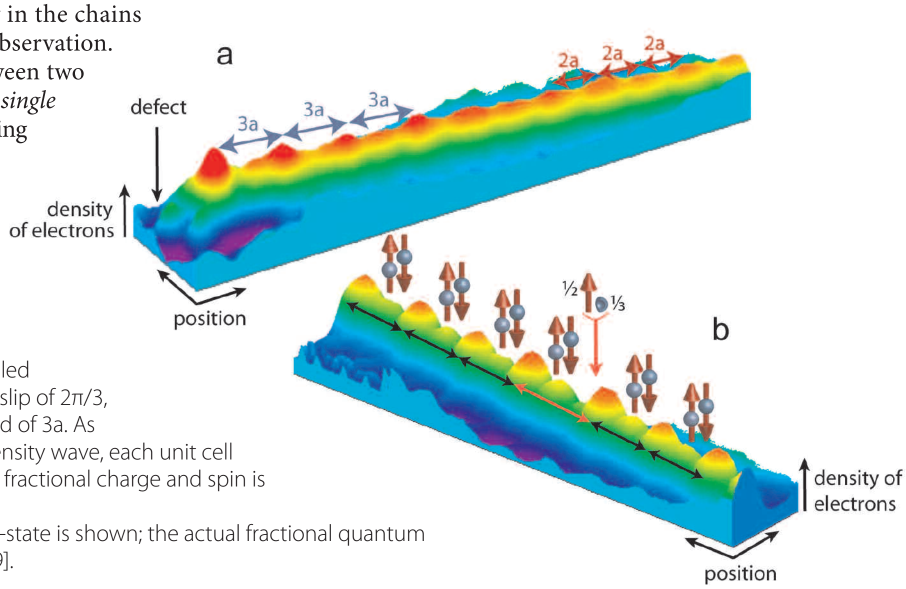
sample temperature to ~40 K, the measurements reveal different characteristics, see Figure 3. First of all, a clear corrugation has developed in the empty state images (Figure 3(b) and (c)). The wavelength of this corrugation is exactly equal to three times the substrate lattice constant a. In the filled state images (Figure 3(d)), the atom wires appear slightly depressed at locations where the empty state image showed enhanced intensity. This contrast reversal with changing tunnel bias polarity is the hallmark of a charge density wave. The charge density is proportional to the density of filled states, and thus the total charge density exhibits a periodic modulation; a charge density wave. Note that the wavelength of this charge density wave is *commensurate*, with n=3, even though the band fillings at high temperature clearly deviate from 1/3 according to the photoemission measurements. The local I-V measurements confirm the existence of a charge density wave: the 40 K STS I-V curve in Figure 3(e) no longer exhibits a slope around zero bias indicating the presence of a band gap. From this STS measurement we can conclude that all three bands exhibit a gap and have lost their metallicity; the surface is completely semiconducting. This is confirmed by the observation of an additional x2 superperiod in between the atom wires with tripled periodicity, see Figure 3(c). The new periodicity is again commensurate with the lattice (n=2). Evidently, two different commensurate charge density waves coexist. They run parallel to the atom rows and are spaced less than one nm apart.

To investigate how these *two* commensurate charge density waves develop from an electronic structure with *three* incommensurate Fermi wave vectors, we have imaged the surface with STM at intermediate temperatures. At 70 K the tripled corrugation is vaguely visible, with significantly enhanced intensity close to defects (not shown, cf. Figure 4 in Ref. [9]). In Figure 4(a), part of an atom wire close to a defect as imaged with the STM at 110 K is represented as a three-dimensional contour. The corrugation of the atom wire exhibits a clear tripled periodicity close to the defect, whereas farther away from the defect, a double-period corrugation is visible. STS data at 110 K reveal a finite slope at zero bias, but the slope is significantly smaller than that at room temperature, see Figure 3(e). The reduced density of states at the Fermi level at 110 K is consistent with a double-period charge density wave in one of the bands, while the other two bands remain metallic. From the 110 K, 70 K, and 40 K STM data, it therefore appears that the triple-period charge density is *defect mediated*, *i.e.* it nucleates at the defects, and grows outward into the bulk of the chain at lower temperatures. However, the doubled periodicity in the chains visible at 110 K is a much more interesting observation. First, it is clear that a competition exists between two different charge density wave orders *within a single atom wire*. These two charge density waves, having different transition temperatures but competing at 110 K, provide the first observation of two competing charge density wave orders in a single atom wire. For example, (bulk) $NbSe_3$ shows two consecutive charge density wave transitions, but those are localized on different "chains" within the unit cell and, consequently, they will have a fundamentally different and much smaller interaction. Secondly, the observation of this second charge density wave within the atom wire allows for a consistent explanation of the low and intermediate temperature electronic structure of a triple-band atom wire system. This explanation will be given in the following Section.

The role of defects

Summarizing the STM and STS observations provides the following data: at 40 K we observe a triple-period charge density wave on the atom wires and a double-period charge density wave between these wires, and at 110 K we observe an additional double-period charge density wave on the wires, all commensurate with the substrate lattice. Photoemission measurements (Ref. [3,8]) reveal three bands, that are 0.27-, 0.51-, and 0.56-filled. The Fermi wave vectors are all incommensurate with the chain lattice. We invoke an interband charge transfer of 0.06 from the 0.56-filled band to the 0.27-filled band to explain these commensurate periodicities. This results in exactly commensurate 1/2-filled and 1/3-filled bands, naturally explaining the observed triple period charge density wave in the atom wires and the double period charge density wave between them. Keeping in mind that these charge density waves appear to nucleate at the defects, we can conclude that these defects act as *dopants* in the atom wires; they change the band-filling, and thus mediate the formation of these two charge density waves. (Our placement of the 0.56-filled band between the atom wires is corroborated by the simultaneous room temperature observation of a local tripled and doubled corrugation on and in between the atom wires very close to the defects, respectively, cf. the discussion and References in Ref. [9].) This leaves the 0.51-filled band responsible for the double period charge density wave that evidently competes with the triple period charge density wave at 110 K.

Apparently, the defects present in the atom wires do not simply disrupt or destabilize the atom wire system. Instead, they appear to *stabilize* the system via a doping mechanism that ultimately favors the commensurate charge density wave state. The energy gain even outweighs a likely strain-energy cost due to the incorporation of these defects.



► **Fig. 4:** (a) 3D representation of an atom wire next to a defect. Close to the defect a tripled periodicity is visible (blue arrows), whereas farther away from the defect a doubled periodicity appears (red arrows).
(b) 3D representation of an atom wire. A clear tripled periodicity is visible, with at one location a phase slip of 2π/3, *i.e.* the distance between two maxima is 4a instead of 3a. As indicated schematically, in the periodic charge density wave, each unit cell (black arrow) contains two electrons, but an extra fractional charge and spin is located at the kink (red arrow).
Note that here the case for a singly occupied kink-state is shown; the actual fractional quantum numbers depend on the filling of the kink-state [9].

Fractional charges

In our experiments at 40 K we observed several phase slips in the triple-period charge density wave, as demonstrated in Figure 4(b). These phase slips or solitons show a jump of $2\pi/3$ in the phase of the triple period charge density wave. It is interesting to note that Schrieffer calculated that such phase slips should have fractional (spin,charge): either $(1/2, \pm e/3)$ or $(0, \pm 2e/3)$, depending on the filling of the localized kink-state [10]. Fractional quantum numbers (with the exception of the spin quantum number) only occur in excitations of a *collective* ground state. A famous example is given by the fractional quantum Hall effect, displayed by a 2D electron gas in high magnetic fields. Here an integer number m of magnetic flux quanta (vortices) is attached to each electron. When the magnetic field slightly exceeds the integer number m of flux quanta per electron, the system is excited by the excess magnetic field and single magnetic flux quanta are "left over". The deficit of charge in these vortices amounts to the fractional charge e/m [11]. Thus, excitations of a collective system of electrons and magnetic flux quanta can produce fractional quantum numbers. Equivalently, the observed solitons represent excited states of the *collective* (electron and phonon) triple-period charge density wave ground state. Fractional charges have been experimentally studied mostly using electrical transport (in the case of the fractional quantum Hall effect) or with optical methods (for bulk charge density wave systems). Such experiments are inherently (bulk-)averaging; signatures of fractional charges can be deduced, but individual solitons are not observed. For the first time, these fractional charges are experimentally accessible through individual solitons in atom wires. STM and STS thus allow for a *real space* study of the electronic structure of these solitons at the atomic scale.

In this regard, the defects in the atom wires again might play an important role: Figure 5 shows two sequential ($\Delta t \sim 180$ s) filled state STM images taken at 40 K. The black circles serve as markers. It is clear that in between the two scans, the configuration of defects indicated by the arrow has changed. A close inspection of another defect in the same atom wire (inside the black rectangle) even shows that this defect is generated when the tip is scanning the atom wire; the defect seems to be present only in the right half of the atom wire. Even though this rearrangement of defects was not intentional, these observations indicate that it is possible to move these defects with an STM tip. It might thus be possible to locate two defects in a single atom wire, separated by for example ten lattice constants. This will induce a phase slip in the triple-period charge density wave, allowing for a systematic study of the electronic properties of these phase slips in preselected locations.

In conclusion, the example provided by the Si(553)-Au surface, nicely illustrates the role of defects in the electronic structure of self-assembled 1D atom wires. They play a pivotal role in the thermodynamic stabilization of the atom wires, and furthermore provide possibilities to engineer specific structures to study the electronic structure of 1D atom wires. Scanning Tunneling Microscopy and Spectroscopy provides a much needed opportunity to determine the precise role of defects in fluctuations and stabilization of 1D atom wires. ■

About the authors

Paul C. Snijders received his Masters Degree in Materials Science at the Delft University of Technology, and investigated these atomic wire systems for his Ph.D. research at the Kavli Institute of NanoScience in Delft.

Sven Rogge received his Ph.D. in Physics from Stanford University in 1997. He works on atomic-scale electronics in semiconductors at the Kavli Institute of NanoScience Delft where he holds a faculty position.

Hanno H. Weitering received his Ph.D. in the physical sciences at the University of Groningen. He has been working in the areas of surface physics and nanoscience and holds a Joint-Faculty Chair of Excellence at The University of Tennessee and Oak Ridge National Laboratory.

References

[1] C. González, P.C. Snijders, J. Ortega, R. Pérez, F. Flores, S. Rogge and H.H. Weitering, *Phys. Rev. Lett.* **93**, 126106 (2004).

[2] P.C. Snijders, S. Rogge, C. González, J. Ortega, R. Pérez, F. Flores, and H.H. Weitering, *Phys. Rev. B* **72**, 125343 (2005).

[3] J.N. Crain, J.L. McChesney, F. Zheng, M.C. Gallagher, P.C. Snijders, M. Bissen, C. Gundelach, S.C. Erwin and F.J. Himpsel, *Phys. Rev. B* **69**, 125401 (2004).

[4] H.W. Yeom, S. Takeda, E. Rotenberg, I. Matsuda, K. Horikoshi, J. Schaefer, C.M. Lee, S.D. Kevan, T. Ohta, T. Nagao, and S. Hasegawa, *Phys. Rev. Lett.* **82**, 4898 (1999).

[5] R. Losio, K.N. Altmann, A. Kirakosian, J.-L. Lin, D. Petrovykh and F.J. Himpsel, *Phys. Rev. Lett.* **86**, 4632 (2001).

[6] J.R. Ahn, H.W. Yeom, H.S. Yoon and I.-W. Lyo, *Phys. Rev. Lett.* **91**, 196403 (2003).

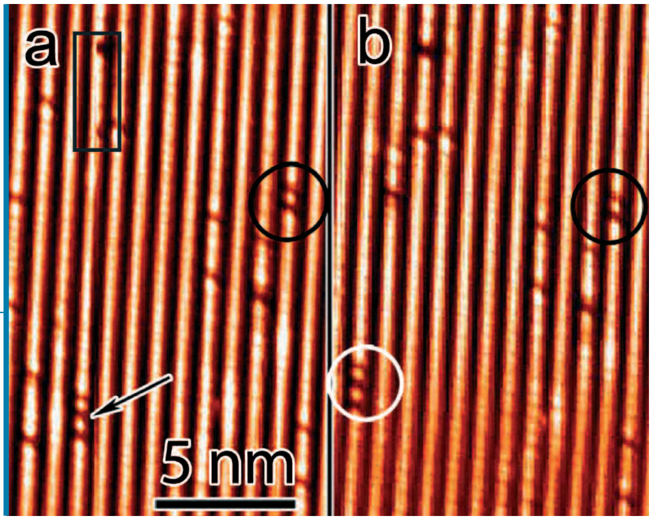
[7] G. Grüner, *Rev. Mod. Phys.* **60**, 1129 (1988).

[8] J.N. Crain, A. Kirakosian, K.N. Altmann, C. Bromberger, S.C. Erwin, J.L. McChesney, J.-L. Lin and F.J. Himpsel, *Phys. Rev. Lett.* **92**, 176805 (2003), see also *Phys. Rev. Lett.* **92**, 089902(E) (2004).

[9] P.C. Snijders, S. Rogge and H.H. Weitering, *Phys. Rev. Lett.* **96**, 076801 (2005).

[10] W.P. Su and J.R. Schrieffer, *Phys. Rev. Lett.* **46**, 738 (1981).

[11] H.L. Stormer, *Rev. Mod. Phys.* **71**, 875 (1999).



▶ **Fig. 5:** (a) and (b) Two sequential filled state STM images at 40 K showing defect relocation. The black circles are position markers, the arrow and white circle are the old and new position of some defects, respectively. The black rectangle shows a defect that is relocated during the scan by the STM tip. Reprinted figures (a) and (b) with permission from Ref. [9], copyright (2006) by the American Physical Society.

PUB

PUB

PUB

PUB