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Fluctuation theorems in small systems
An inspiring physics teacher

41/2
2010

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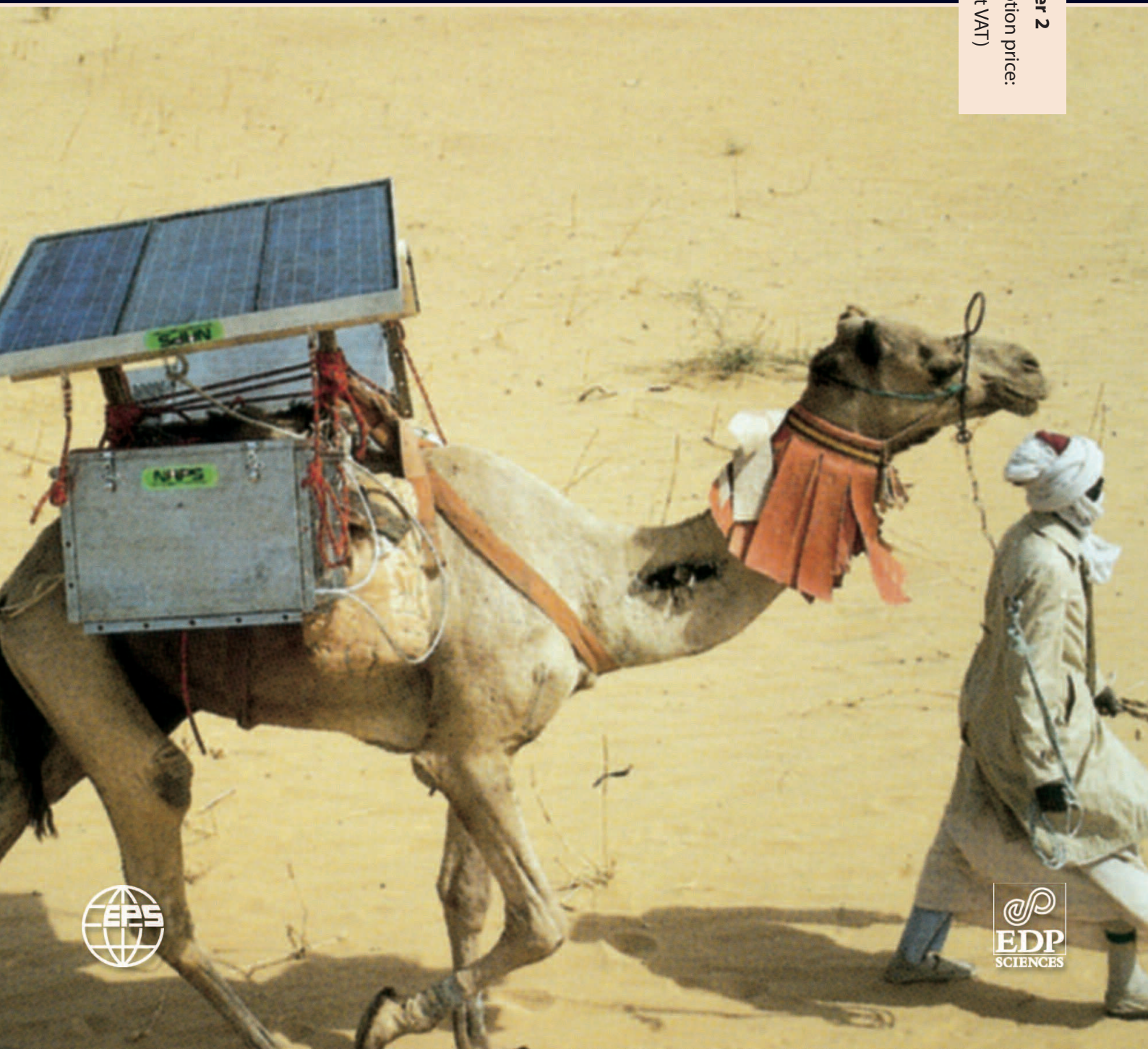

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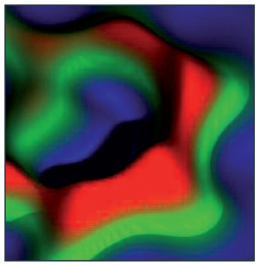
Cover picture: One of the monumental health projects of our time has to be the effort to bring vaccines into remote, rural regions of the world. Vaccines must be kept cool, and in remote rural regions where it's too hot to begin with, a reliable source of electricity is usually not a feature. Photo courtesy of Naps Systems of Finland.



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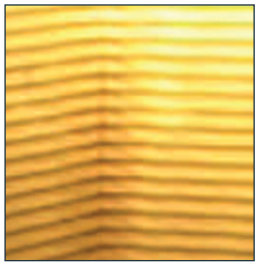
Textbook images of a molecule



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The ^{7}H resonance

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Fluctuation theorems in small systems

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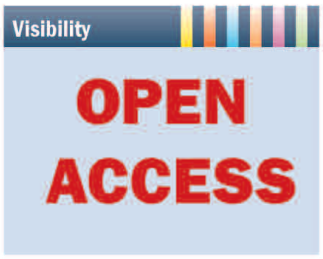

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EPS anno 2009

2009 was the second year of the world financial crisis, but with slight signs of recovery. Governments have adopted two approaches to this problem: most tried to cut expenses, including those for research; a few tried to invest in science as the best method to stimulate progress, development and the future prosperity of society. Even the Copenhagen 2009 climate conference was not especially successful due to the implications for economies.
Three issues need to be considered in the future world economic recovery & development:

- **Education of the next generations**, accompanied by promotion of science & engineering and the scientific interest of the young population, along with efforts to educate the whole population (promotion of science).

Science is not only at the heart of learning [1] but it serves as the source of the innovative, practical knowledge required to maintain research & technological development. Knowledge can stimulate the growth of environmentally friendly industry on the one hand but it should also provide the basis for social development founded on understanding, not opinions.
It is fundamental for humanity to maintain a scientific (physical), realistic point of view on all phenomena, including the economy and climate as well as healthcare and even culture. In this context many methods of education are essential: for example, conferences organized for exchange of knowledge and experience, and the education and training of scientists through appropriate doctoral studies; another key factor is the constant in-service training of teachers including cooperation of scientists with teachers [2]; and last but not least should be mentioned context- and inquiry-based school teaching .

- **Great challenges** that require further research and technological development are the need to achieve sustainable energy [3], and clean industry and the environment.

- **International & global cooperation** are required to analyse and inform society about global threats related to environmental change, such as possible sun activity, seismic activity, the security of information transfer, and the importance of physics for developments in medicine and healthcare, etc.

All other issues appear secondary to these three. What can be the contribution of EPS in facing these problems?
EPS **Divisions and Groups**, and **Committees** organise important professional activities in physics.
Divisions and Groups have organised more than 13 conferences and given 15 prestigious prizes to honour brilliant physicists, making their achievements more visible.

notes

[1] Lisa Jardine BBC News Magazine 22 January 2010: http://news.bbc.co.uk/ go/em/fr/-/2/hi/uk_news/magazine/8474551.stm
[2] Very interesting article about GB, but situation is much more critical in almost all parts of Europe. http://fps.epscommittees.org
[3] The EPS, EuCheMS, E-MRS and the ESF organise the European Energy Conference, from 20-23 April 2010 in Barcelona. www.e2c-2010.org

Committees have worked on strategic problems ranging from education, conferences, grants, and publications to the future of our Society. The creation of the new EPS Young Minds Committee will increase interaction with the next generation of physicists.
The **Executive Committee** has worked extensively on a new strategy to face these challenges and to adapt the Society to contemporary needs. The first effects can be clearly seen – a new strategy, new web page, new face of EPN, growing impact factor of EPL, new committee and new Education Platform. The Secretariat with the Secretary General is preparing the changes needed to adopt new work methods.

To conclude, I should mention **EPS finances**. The Executive Committee will not recommend an increase in membership fees despite there being no increase for the past 5 years, leading to an approximately 20% decrease in value of the fee due to inflation. This leads to the necessity for financial restrictions. This means that EPS must adapt its activities and services to members to be more in line with what can be afforded, and to seek for alternative methods of financing.

Let me finish with my sincere thanks to all working for the EPS. Let me mention only a few: starting with the past presidents Martial Ducloy (Forum Physics and Society), Martin Huber (EPL), Ove Poulsen (Forum Physics and Society, Publishing Platform) through editors of EPN, Claude Sebenne and Jo Hermans, and the editor of EPL, Volker Dose, to all members of the Executive Committee especially the outgoing members, Angela di Virgillo, Victor Valesco, Victor Urumov and Peter Melville. And last but not least it is my pleasure to thank the past president Fritz Wagner. His energy and determination in conducting and leading EPS has been a difficult example to follow.
I also thank all members of the office staff and in particular the Secretary General, David Lee who has engaged in services to EPS so deeply that often he is identified with the Society. ■

Maciej Kolwas,
President of the EPS

After the Executive Committee

29-30 January 2010 (Gent, Belgium)

The Executive Committee was welcomed to Gent University by H. Dejonghe, Dean of the Faculty of Sciences. During the meeting a number of important items were on the agenda.

• **Strategy Discussion:** a discussion on EPS strategy would be included on the Council agenda together with a proposal to form a working group to study EPS strategy and structure.

• **Alliance for Physics Publishing:** work to create a platform of the journals EPL, EPJ, JPhys and NJP and their publishers DPG, EPS, IoP, SFP and SIF and Springer continues. The current APP working group should be given a mandate to define the timeframe to finalise the terms of reference and initial activity plan.

• **Large Facilities Technical Network:** the Executive Committee approved the creation of the Internet tools for the implementation of this Network, which is designed to allow researchers and science managers to share experience in the management of large research projects. 31 institutes have expressed interest in participating in the LFTN.

• **Joint Solar Physics Group:** draft statutes of the group will be submitted to Council for approval.

• **Asia Europe Physics Summit:** The ASEP summit takes place from 24-26 March in Tsukuba, Japan and is co-sponsored by the EPS and AAPPS. One of the outcomes of the meeting is a request to the EPS and the AAPPS to study appropriate methods to increase cooperation among the European and Asian physics communities.

• **EPS Education Platform:** there are currently many educational activities under the auspices of EPS, or related to the EPS. To effectively coordinate EPS education activities 14 individuals representing 12 organisations and projects involved in physics education met in Mulhouse and formed the EPS Education Platform.

• **European Specification Description for Physics Bachelor Studies:** the Executive Committee approved this document, prepared by **H. Ferdinande**, as an EPS report. It summarises the specifications for a Bachelor degree in physics.

• **EPS Young Minds Project:** the Executive Committee approved the project to create groups of young physicists that organise communication activities at the local level under the sponsorship of EPS.

• **Gero Thomas Prize:** the Executive Committee confirmed that it will be awarded annually and that MS, IMs, D/G should be urged to make nominations.

• **EPL:** the journal has progressed considerably in the past three years under the direction of **Volker Dose** as Editor in Chief. Indicators that show this are the number of submissions, number of institutions that have access to EPL, and scientific quality. Looking at the immediacy index (*i.e.* the number of times an article is cited in the calendar year that it was first published in) shows a significant increase in the citations in EPL.

▲ Gent, BE

The Executive Committee approved the nomination of **Michael Schreiber** as the Editor in Chief of EPL. He will replace **Volker Dose** to whom the Executive Committee expressed its thanks for all of his hard work and devotion to the journal. ■

David Lee,
Secretary General

Revisiting simple experiments:

the MUSE project, a stimulus to go beyond mere excitement and avoid rituals

It is widely agreed that simple, enjoyable experiments successfully involve students in the field of physics while also serving as an entertaining introduction to this field for those unfamiliar with physics.

MUSE (More Understanding with Simple Experiments: http://education.epsdivisions.org/muse) is a project which has recently been set up by a group in the Physics Education Division of the EPS with the goal of helping pre-service and in-service teachers to extend their ideas and offering them more pedagogical choices in regard to physics.
Why not stress Archimedes' up-thrust and also include its reciprocal force (termed Archimedes' down-thrust by this unorthodox MUSE)? What is the relationship between pressure at the bottom of a container filled with water and the weight of the water? Does an object in a static situation always exert a force equal to its weight on a scale? Was Marie Curie right when she strongly suggested that the only force acting on water in a test-tube over a tank of water resulted from atmospheric pressure and the water's weight? Why is such a reductive approach also common for a glass of water covered with a piece of cardboard and then inverted?
These seemingly elementary questions are illustrated in simple experiments accompanied by educational tips and information, including:

- possible conceptual targets relating to different variants of the experiment (*e.g.* a glass of water turned upside-down or put in a horizontal position);
- common difficulties students experience and ways of addressing these;
- ritualistic and possibly erroneous explanations with justified alternatives or complements.

The documents provided will be new texts written by the authors of the project as well as selected references to videos or papers that seem particularly relevant to the questions raised and are briefly explained in the presentation.
Work on the theme of fluids is still in progress (*e.g.* water jets, siphons, floating coins), and other projects will soon follow (*e.g.* light and vision). Any interaction and discussion is welcome! Anyway, do visit the site and aMUSE yourself! ■

▼ In a horizontal position, the water does not flow out of the glass either

Gorazd Planinšič, (gorazd.planinsic@fmf.uni-lj.si), **Elena Sassi** (sassi@na.infn.it), **Christian Ucke** (christian.ucke@web.de), **Laurence Viennot** (laurence.viennot@univ-paris-diderot.fr)

Letter

Comment on R.A. Ricci's article

In EPN 40/5, 13 (2009) a feature article by R.A. Ricci has been published entitled "A daring interpretation of binary fission". The paper reviews ideas on fission theory having been proposed by C. Ythier and G. Mouze from the University of Nice/France.

In the abstract it is said that 69 years of research has not led to an explanation asymmetric fission in the lighter actinides and symmetric fission of ^{258}Fm and heavier nuclei. The Ythier-Mouze theory claims to have finally found a solution to this enigma. This is a turnaround of historical facts and – pushed by many colleagues – with the present letter I want to fiercely object to the methods applied and the statements made in the Ythier-Mouze theory.

The theory of Ythier-Mouze is a succession of assumptions with no sound experimental or theoretical substantiation. In particular the results on mass distributions of actinides have found an accepted interpretation since decades. To be succinct I will discuss only one of the basic ingredients of the theory and one result.

To start with, in the article it is said that the fission reaction time is $\Delta t = 1.77 \cdot 10^{-25}$ s and, invoking the uncertainty relation, this is equivalent to a mass spectrum of 4 nucleon masses. The conclusion is drawn that "any discrete mass value should be replaced by a "mass spectrum" having a width of 4 atomic mass units". Therefore, instead of single masses there should always be a quadruple of masses to be observed in fission. However, despite the numbers of fission experiments being countless, the conjectured quadruples of masses have never been seen. For the "experimental proof" of their conjecture Ythier-Mouze refer to a study of cold fission in thermal neutron fission of ^{236}U* where, amongst others, isotopic mass distributions in a narrow window of 2 MeV for the total kinetic energy are shown. For some of these distributions in fact 4 mass lines show up. But there is no mystery or new discovery. It just means that, constrained by energy, the nuclear charges considered contribute to 4 mass splits. For other charges or energies the number of mass lines is completely different. The crucial point is that in all binary fission events, including those addressed by Ythier-Mouze, per event there is always only one heavy and one complementary light fragment and never four fragments with neighbouring masses. A fundamental assumption of the theory is hence based on the erroneous misinterpretation of an experiment. Any conclusions drawn are therefore more than doubtful.

The statement in the EPN article that one had to wait for the daring interpretation of asymmetric and symmetric fission by Ythier-Mouze is not fair to generations of nuclear physicists. Asymmetric mass distributions were in fact a puzzle for some time but since the advent of the shell model there is no longer a mystery. Phenomenological models for asymmetric fission were successfully proposed more than 40 years ago and nowadays even fully microscopic theories are available. Likewise symmetric fission in the Fermium isotopes was conjectured some 50 years ago and nowadays even fine details like bimodal fission are understood. Obviously not all secrets of the complex fission process have been disclosed but certainly the Ythier-Mouze theory will not be of any help or guidance for future work. ■

Yours sincerely,

F. Gönnenwein,
Eberhard Karls Universität,
Tübingen, Germany

R.A. Ricci responds
to the comment of F. Gönnenwein

I will divide my answer into two parts. First of all, concerning the more general (and *historical*) aspect of the description of nuclear fission phenomena, I have honestly to make clear that I didn't mean to disregard (nor to be unfair to) the fundamental work done by "*generations of physicists*", among which I have good friends with whom I did exchange a continuous mutual appreciation. Unfortunately, the sentence that appears in my introduction, concerning the fact that "*after 69 years there was no explanation of the asymmetric fission in light actinides and of the symmetric one in ^{258}Fm and heavier nuclei…*" was only a preliminary version which should have been replaced by a new one. Unfortunately, due to some technical computing mistake (different secretary offices), it was never sent for publication the way I wanted. The corrected version should have read: "*During 69 years various approaches and model descriptions have been used to describe, in particular, the asymmetric fission in very light actinides and the symmetric fission of ^{258}Fm and heavier nuclei as well as the observed width of regions of appreciable yield of the fragments and its variation as a function of the mass AF of the fissioning nucleus.*"

In apologizing for this inconvenience, I come to the essential aspect, saying that, nevertheless, there could be other new approaches which, apart from some *redundant* emphasis, could be of interest in explaining such phenomena. In fact, the "*daring*" (as I called it) interpretation of Mouze-Ythier attracted my scientific curiosity for some reasons. What they have found, or claim to have found, is a (very) simple formula *which perfectly describes the region of appreciable yield, in the mass distribution of the light fragment A_L of "any asymmetric and symmetric fission"*. This would be a novelty, in my opinion (which could be wrong since I am not a specialist of nuclear fission), to be discussed anyway. Indeed, they observed that the lower limit is $A_{L(min)} = 82$ in the asymmetric case and $A_{L(min)} = 126$ in the symmetric case, while the higher limit is $A_{L(max)} = A_{CL} + 82$ in both cases! The only quantities appearing in these expressions are the well-known magic numbers 82 and 126, the mass A_{CL} of the cluster of the fissile nucleus clusterized into ^{208}Pb + A_{CL} and the number *82* of nucleons lost by the ^{208}Pb core as it becomes the A = 126 nucleon core of the nascent heavy fragment. This is what I accepted as a novelty.

On the other hand, the process followed by M-Y to estimate the rearrangement time of the fission reaction *through the mass-width of the fragments is quite similar* to that used to estimate *the lifetime of the hadrons* (decay by strong interaction in 10^{-24} - 10^{-22} sec.) *through their "energy-width"*, since in both cases such times cannot be directly measured. The 4u value results from the analysis of the mass distribution obtained by the cold fission specialists. I do not think that M-Y have tried to fetch the "*quadruples of masses*" as commented by Gönnenwein. Following their explanation, they have added the events counted in each of the histograms at masses 102, 103, 104, 105, 106, 107 of Signarbieux's distribution, then plotted the logarithm of these sums as a function of the mass and finally observed that the continuous Gaussian curve so obtained had a width (FWHM) equal to 4u. Moreover they have recently brought to my attention that the same method applied to the cold-fission data of Gönnenwein leads to exactly the same result, with even better statistics. Therefore the new approach is based on the broadness of the mass-width of the fission fragments. This fact of course may be controversial and Gönnenwein's comments belong to a legitimate difference of view.

I will not enter into other details which, if necessary, could be better explained by Mouze and Ythier who, by the way, are the real authors of the new approach. Personally I could add, taking also into account the also daring suggestion of a nucleon phase in nuclei, at certain energetic and mass situations, that it will not be the first time that some exotics of nuclear matter would appear. One may recall that the standard shell-model had to be revised in view of collective behaviour and nuclear phase-transitions and that, as a function of mass and distance from the stability line, even the isospin and spin-orbit coupling together with the concept of magic number can lose their importance. Moreover even the characterization of protons and neutrons as fermions is surpassed by the nucleon-pair approach as bosons in the well-established Interacting Boson Approximation.

Of course my presentation was based on a personal opinion. A fair scientific controversy in such cases could be welcome and, anyway, does not affect my appreciation to the editors who did accept to publish my paper, and my consideration and esteem for Prof. F. Gönnenwein. ■

With my best regards,

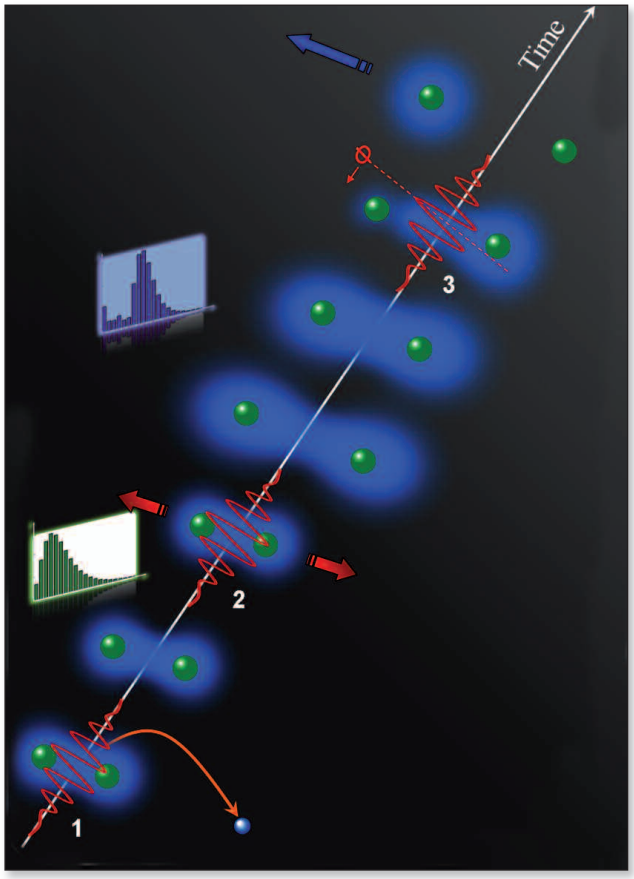
Renato Angelo Ricci,
Professor Emeritus, University of Padova. Honorary President Italian Physical Society, Fellow EPS

Highlights from europeans journals

ATOMIC AND MOLECULAR PHYSICS

Enhancing **electron localisation** via vibrational wavepacket control

Quantum control of chemical reactions in molecules is a prominent quest in modern physical chemistry. Such control requires precise manipulation of electronic wavepackets, which typically evolve on an attosecond (10^{-18} s) timescale. A powerful technique for controlling electronic dynamics during molecular dissociation is to use few-cycle femtosecond (10^{-15} s) laser pulses of infra-red radiation. Through controlling the relative phase relationship, ϕ, between the carrier field and pulse envelope, and using a sequence of such pulses, a new scheme has been identified for directing the localisation of the electron upon molecular break-up, *i.e.* whether the electron goes to the 'left' or 'right' nucleus.



The above scheme has been outlined using simulations of the deuterium molecular ion (D_2^+) exposed to a sequence of 7 fs pulses. Pulse 1 ionises a D_2 target to launch a coherent D_2^+ vibrational wavepacket. Pulse 2 is carefully timed to non-destructively manipulate this bound wavepacket into a new vibrational distribution. Pulse 3 then dissociates the molecular ion, where careful choice of delay time allows the dissociation to be maximised and tuning of ϕ leads to strong localization of the electron to a particular nucleus.

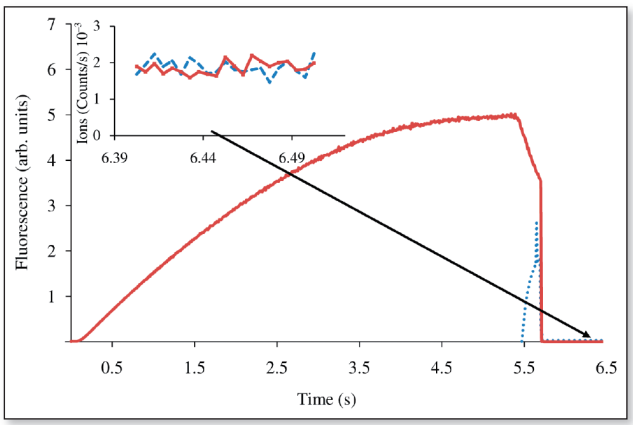
With carefully chosen pulse parameters to optimally control the vibrational wavepacket dynamics and the final dissociation event, the final 'left:right' ratio of the electron localization can exceed 10:1. ■

C.R. Calvert, **R.B. King**, **W.A. Bryan**, **W.R. Newell**, **J.F. McCann**, **J.B. Greenwood** and **I.D. Williams**, 'Multi-pulse scheme for enhancing electron localization through vibrational wavepacket manipulation', *J Phys B: At Mol Opt Phys* **43**, 011001 (2010)

ATOMIC AND MOLECULAR PHYSICS

A stable metastable **helium–rubidium mixture**

The relatively new ability to combine gasses at ultra-low temperatures and high densities has proven to be an exciting playground for fundamental physics. To date, most studies performed with ultra-cold mixtures have involved alkali atom species in which the inter-atomic collisions result in only small losses. For the first time we combine metastable helium atoms (He*) that exist in an excited-state and carry 19.8ev of internal energy, with ground-state rubidium atoms at ultra-low temperatures. Rubidium atoms have an ionisation energy of ~4ev thus a collision with a He* atom is sufficient to Penning ionize the rubidium atom. Surprisingly, in a spin-polarised mixture the rules of quantum mechanics can inhibit collisional losses within the mixture, as the process of Penning ionisation cannot conserve spin.



▲ **MOT fluorescence traces, rubidium (red curve) and He* (blue curve) indicate both MOTs being loaded. At ~5.7 seconds the mixture is transferred into a magnetic trap. The inset shows no additional Penning ions are detected for the spin-polarised mixture (red curve) when compared to an ion trace when only He* is present (blue curve).**

By loading both clouds of atoms from a magneto-optic trap (MOT) into a magnetic trap (where both species are spin polarised), we probe the suppression of Penning ions. Within the noise levels of our experiment we observe no increase in Penning ion production due to the presence of rubidium thus demonstrating at least a factor of 100 suppression in Penning ions due to spin polarisation. In the future we will attempt to create the first excited-state/ground-state Bose-Einstein condensate mixture. Hopefully, our initial measurements will stimulate interest amongst scattering theorists, as little is known about the molecular interactions of ultracold He* and rubidium. ■

L.J. Byron, **R.G. Dall**, **Wu Rugway** and **A.G. Truscott**, 'Suppression of Penning ionization in a spin-polarized mixture of rubidium and He*', *New Journal of Physics* **12**, 013004 (2010)

STATISTICAL PHYSICS

Logical independence and quantum randomness

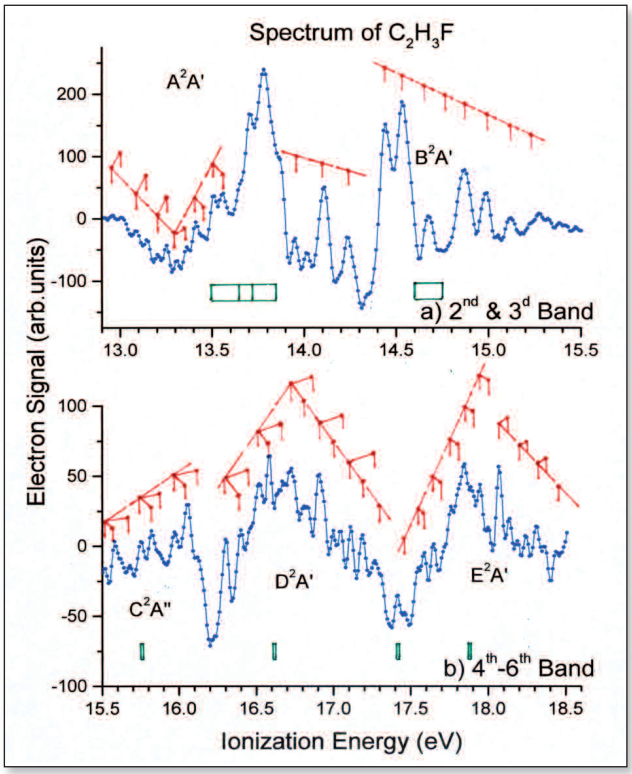
Imagine a game show with a candidate and a quiz master. Unfortunately, the candidate has a storage capacity of only one single bit. In other words, he is able to memorize the solution "yes" or "no" to only one single binary question. The rule of the game is that the candidate cannot refuse a question and has to give an answer to every yes-no question he is asked by the quiz master. Say, the candidate starts with the one-bit knowledge that the statement "France is in Europe" is true. However, the first question by the quiz master is about a *logically independent* statement, namely whether it is true or false that "Gordon Brown is Prime Minister of the UK". The poor person only knows about France being in Europe and thus has to randomly guess an answer "yes" or "no".
The situation is similar in quantum mechanics. Electrons, for instance, are spin-1/2 particles, and their spin is always up ("yes") or down ("no") along some direction. If the spin is up along a certain direction, say *z*, then – due to Heisenberg uncertainty – it is totally undefined along the orthogonal complementary directions *x* and *y*. A group of quantum physicists (T. Paterek *et al.*) from the University of Vienna and the Institute for Quantum Optics and Quantum Information (IQOQI) propose to view the electron's situation in the same way as the quiz show candidate. They find a precise link between spin measurements along different directions and logically independent mathematical questions. The electron can encode the answer to only one of these questions. Whenever the experimenter asks a question that is logically independent from that particular one, the outcomes are random, as there is no information whatsoever to specify the result. ■

T. Paterek, **J. Kofler**, **R. Prevedel**, **P. Klimek**, **M. Aspelmeyer**, **A. Zeilinger**, and **C. Brukner**, 'Logical independence and quantum randomness', *New Journal of Physics* **12**, 013019 (2010)

ATOMIC AND MOLECULAR PHYSICS

Autoionization and non-adiabatic coupling in **molecular photoionization**

Understanding chemical reactivity requires a detailed knowledge of reactant properties at the molecular level. Ionic reactivity is at the core of powerful analytical technique such as mass spectrometry. Investigating ion production mechanisms and the partitioning of the electronic and vibrational energy is therefore essential. Photoionization is a convenient way to produce cold as well as excited molecular ions. For many ions, only the properties of the ground electronic state are known in detail. Excited states are nevertheless essential to promote reactivity. The authors present the most detailed investigation to date on the photoionization of vinyl fluoride (C_2H_3F), combining four approaches: photoelectron spectroscopy at 21.21eV, threshold photoelectron spectroscopy (TPES), constant ion state spectroscopy (CIS) and high-level *ab initio* quantum chemical calculations. In addition to extending the knowledge on the ground electronic state, these techniques provide relevant information on six excited electronic states. The focus is on the identification and assignment of the vibronic levels, on the role of autoionization (coupling between neutral excited states and ionization continua), and the identification of non-adiabatic couplings (avoided crossings and conical intersections) between ionic electronic states,



▲ **Electron signal resulting from photoionization to electronic excited states of $C_2H_3F^+$. The vibrational structure (red markers) has been amplified by a continuum subtraction procedure. The green areas locate the fragment appearance energies.**

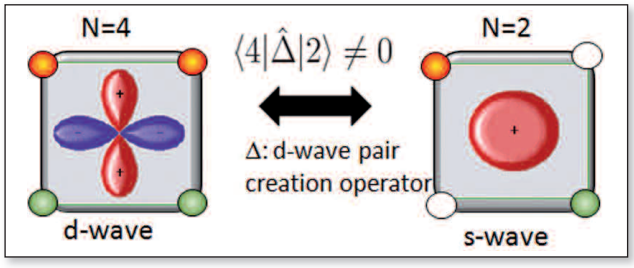
which are essential to promote internal energy conversion. In the top figure, two vibrational modes are identified for the $\tilde{A}^2A'$ state of $C_2H_3F^+$ (12.9–14.3eV) and are assigned to F-CC bending and CF stretching in line with the theoretical predictions. These vibrational progressions are strongly perturbed in the 13.6–13.9eV region by an avoided crossing between the $\tilde{A}^2A'$ and $\tilde{B}^2A'$ states. Such phenomena are responsible for 80% of the fragmentation yield. TPES and CIS spectra reveal that autoionization strongly favours the production of electronic excited states at threshold, compared to the ground state. ■

R. Locht, B. Leyh, D. Dehareng, K. Hottmann and **H. Baumgärtel**,
'A photoelectron spectroscopic investigation of vinylfluoride (C_2H_3F): the HeI, threshold and CIS photoelectron spectroscopy', *J. Phys. B: At. Mol. Opt. Phys.* **43**, 015102 (2010)

OPTICS

d-wave superfluidity in two-dimensional optical superlattices

While the exact pairing mechanism in cuprates and similar materials is still not understood, it is believed that the basic physics is contained in the simple 2D Hubbard model, in which fermionic particles move on a lattice and repel each other when they occupy the same lattice site. For the Hubbard model, d-wave pairing is expected to occur from an effective attraction caused by the exchange of spin fluctuations. Nevertheless, whether this pairing can give rise to long-range order and superconductivity is an open question. Here we propose an experimental scheme in which recently demonstrated methods for realizing optical lattices and superlattices are combined to create and to detect, in a controlled way an ultracold-atom d-wave superfluid. Our scheme starts from arrays of isolated plaquettes, which incorporate the required d-wave correlations on a short length scale.



▲ **A plaquette is the minimum system that exhibits d-wave symmetry. When loaded with four fermions the ground state is d-wave symmetric while when loaded with 2 the ground state exhibits s-wave symmetry. Consequently, the two states have a non-zero matrix element with the d-wave pair creation operator. Here we propose to load an array of plaquettes with cold fermionic atoms and use this set up as the starting point to engineer in a controllable way a d-wave superfluid by coupling the plaquettes.**

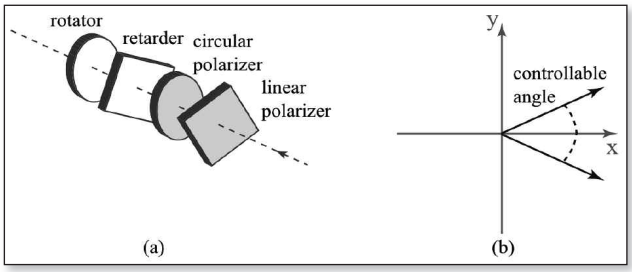
By tuning the parameters of the potentials, these plaquettes can be coupled to achieve long-ranged-wave superfluid correlations, finally arriving at the generic Hubbard model. ■

A. M. Rey, R. Sensarma, S. Fölling, M. Greiner, E. Demler and **M. D. Lukin**,
'Controlled preparation and detection of d-wave superfluidity in two-dimensional optical superlattices',
EPL **87**, 60001 (2009)

OPTICS

White polarization sandwiches

To learn how light propagates through an anisotropic medium, we often look at this medium's eigen-waves. In a birefringent crystal, for example, we can decompose the light into ordinary and extraordinary eigen-waves, each with a different refraction index. The polarizations of the eigen-waves (or eigen-polarizations) are orthogonal in most optical crystals, but they may become non-orthogonal in complex optical elements that combine several anisotropy types (dichroism and birefringence). Complex anisotropy combinations cause complex behaviour of such elements and make them interesting for study in polarization optics. The present article theoretically considers a class of elements with non-orthogonal eigen-polarizations that they called white polarization sandwiches. Any white sandwich is anisotropic: it changes the polarization of incident light. But a combination of two identical white sandwiches is isotropic and does not effect the polarization. It means mathematically that white sandwiches are non-trivial square roots of unity, and they belong to the general class of non-hermitian objects considered not only in optics but in quantum mechanics and other areas of physics.



▲ **White sandwiches are synthesized by combinations of four basic elements (a). The angle between two linear eigen-polarizations of a white sandwich can be controlled (b).**

Using a general four-component model of polarization elements, one analyzed white polarization sandwiches and showed how to synthesize these elements by combinations of conventional polarization elements: polarizers, retarders, and rotators. They showed that the form, orientation, and rotation direction of the eigen-polarizations of white sandwiches can be controlled by changing the properties of the constituent elements. For example, a white sandwich consisting of a partial linear polarizer and a 90-degree retarder has two linear eigen-polarizations, the angle between which can be controlled by changing the relative absorption of the polarizer. ■

O. Sydoruk and **S.N. Savenkov**,
'White polarization sandwiches: optical elements with non-orthogonal eigen-polarizations', *J. Opt.* **12**, 035702 (2010)

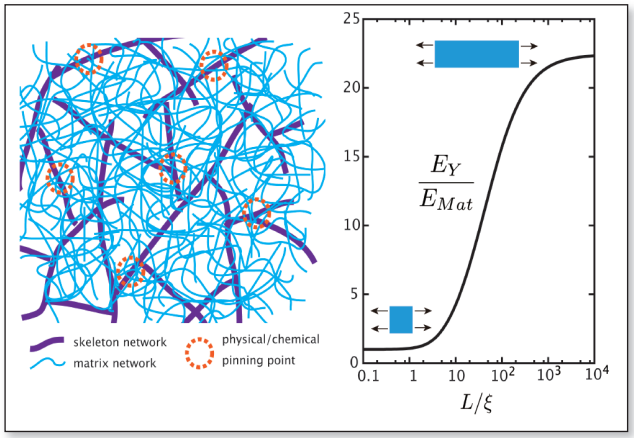
CONDENSED MATTER

Nano-scale composite matter: elasticity is size-dependent

Composite materials in industrial products are produced by dispersing rigid particles or fibres (reinforcement phase) into a uniform solid (matrix phase). Elastic properties of the entire system are given by spatial average of elastic behaviours of the two phases. Existence of sharp interfaces between the phases is the major premise for the averaging. There is another class of composite materials where two components are mixed on the molecular scale and the interface cannot be identified definitely. An example of this class is a cytoskeleton of eukaryotic cells, a composite meshwork of rigid and flexible biopolymers, which provides distinct mechanical properties to living cells. This observation has been exploited in the design of synthetic materials; Among a double-network gel, an isotropic interpenetrating stiff and flexible polymer network, achieved much improved toughness.

In the recent paper, we developed a linear elasticity theory of such composite materials. In that model, a flexible polymer network constitutes a matrix phase and stiff filaments act as a skeleton (fig: left). Such an internal structure, generic to composites, yields an intrinsic length scale ξ by the competition between collective elastic deformations of both the components and their mutual displacements, leading to length-dependent elastic constants (fig: right). For $L < \xi$, where L is a system size, the Young's modulus is nearly identical to that of the matrix and is small, but for $L >> \xi$, it gets much larger due to the stiff backbone as the composite behaves as a single material. This unique size-dependent elasticity is expected to be a fundamental property among those asymmetric composites, independent of their detailed architectures. ■

Hirofumi Wada and **Yoshimi Tanaka**, 'Mechanics and size-dependent elasticity of composite networks', *EPL* **87**, 58001 (2009)

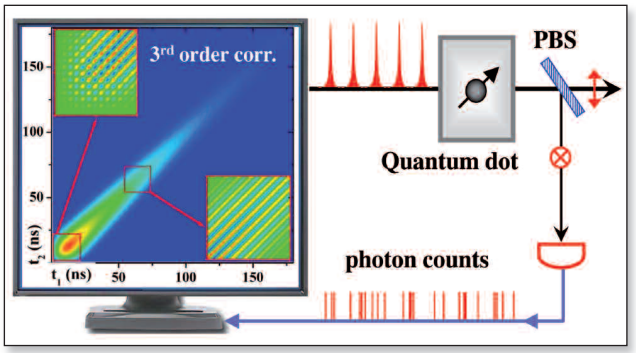


▲ **(left): Microstructure of a binary network composite (cartoon). (right): Size-dependence of the composite's Young's modulus, E_Y, rescaled by the matrix modulus E_{Mat}, calculated from our model elastic free energy.**

QUANTUM PHYSICS

Revealing quantum dynamics by **weak measurement**

Tracing the dynamics of a single quantum object is difficult for two reasons. First, the interaction between a probe and the object is usually weak, and therefore the measurement yields much less information than a bit per shot. Second, measurement will cause a quantum state to collapse randomly. There is, however, tradeoff between the two restrictions, related to the quantum complementary principle: Under weak measurement with a low information yield rate, the rate of state collapse and hence the disturbance to the object are accordingly low. In light of this, the present paper puts forward an idea of reconstructing the dynamics of a quantum object by analyzing the random output of a sequence of weak measurement, or more generally, time-distributed weak measurement.



▲ **(Left) Different time separations of the third-order correlation of sequential weak measurements reveal a range of phenomena in a spin precession: rapid dephasing due to static inhomogeneous broadening and relatively slow decoherence in dynamical environments.**

The authors consider a system relevant in quantum computing and spintronics, namely, a single electron spin in a quantum dot, and employ the tiny Faraday rotation imparted by the spin to the polarization of a sequence of laser pulses as a proof-of-concept weak measurement. The setup involves only linear optics and photon counting, requiring no initialization or spin rotation as in conventional spin resonance spectroscopy. The photon counts appear as shot noise, but the correlation functions reveal the precession of the spin under a magnetic field with decaying amplitude. Interestingly, the spin decoherence is isolated from the inhomogeneous broadening effect in the third-order correlation function. The correlation analysis of time-distributed quantum measurement complements the noise-spectrum method rooted in Einstein's work on the dissipation-fluctuation relation. ■

R-B Liu, S-H Fung, H-K Fung, A.N. Korotkov and **L.J. Sham**, 'Dynamics revealed by correlations of time-distributed weak measurements of a single spin', *New Journal of Physics* **12**, 013018 (2010)

* **Branislav Cvetković** [1] and **Zoran Hadzibabic** [2]
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* DOI: 10.1051/epn/2010201

NATAŠA ČALUKOVIĆ

AN INSPIRING PHYSICS TEACHER

Nataša Čaluković is the leading authority in Serbian pre-university physics education. She has written more than twenty innovative textbooks. Her students at the Mathematical High School in Belgrade regularly win medals at the International Physics Olympiads, continue their education at the most prestigious universities in the world and build successful scientific careers. What is her secret?

After graduating from the Mathematical High School in 1974, Nataša studied physics in the Department of Mathematics and Natural Sciences at the University of Belgrade. She was an extraordinary student, and both her professors and her peers were convinced that she would pursue a successful scientific career. It was to everyone's surprise when she instead decided to teach physics at her old high school. When asked today why she chose teaching high school physics over a scientific career, she promptly answers that teaching is what fulfils her with joy and pride, and that she sees her contribution to science in the number of young people she has motivated to study physics. And by that measure, her contribution to science is remarkable.

Nataša's work – the testimony of her former students

What is so specific and important about her work that makes her so different and special among the myriad of her colleagues? In the acknowledgments section of his PhD thesis (MIT 1998) Petar Maksimović says that he was "especially proud to be a student of Nataša Čaluković, who showed him how to enjoy physics". Nikola Sibalić, a winner of the gold medal at the 2009 IPhO, says that "Nataša always encourages people to question things and think deeply about ideas and problems. After the first couple of classes, you get used to having dozens of questions constantly zipping through your mind: *When does this solution make sense? What happens if you change this parameter? Why is that true? What are the limiting cases? What is an approximate solution? What's going on here, how to find that, and what can be neglected? Why is this incorrect?* You start observing the world more closely, and it reveals itself to

▲ Serbian team at the IPhO 2005 in Salamanca with team leaders and teachers. Nataša Čaluković is fourth from the left.

Intriguing questions for talented students

Why is the trajectory of a rain drop a straight line, and the trajectory of a stone a parabola?

Nataša Čaluković treats talented students with special care. Here is an example of a puzzle which she uses to motivate even the most talented students.
On the window of a train moving with constant velocity $\vec{u}$ traces of rain drops are "inclined straight lines". The motion of a rain drop can be considered as a "sum" of two motions: horizontal with constant velocity $-\vec{u}$ and vertical fall (we consider the situation when there is no wind). The motion of stone with initial velocity in horizontal direction is also combined of uniform horizontal motion and vertical fall. However, the trajectory of a stone is not a straight line, it is a parabola.

you in its full splendor and diversity. Her approach to physics is really a mind-opening experience".

Nataša is deeply aware that physics cannot be learnt just from books, and that creating new science relies on a dynamic interplay of discussions, calculations and experiments, and requires many trials and errors. All this takes place in Nataša's lectures, and rather than being taught as a matter of fact, physics is being rediscovered by high school students in a small lecture hall. That is really a unique experience, and it is hard to forget the pleasant and stimulating atmosphere of her classes. She always encouraged us to work together and explain ideas to each other, question the physical meaning of the mathematical solutions, and think of gedanken experiments.

The training in rigorous problem solving is a traditional strength of the Mathematical High School, but one of Nataša's specialties are tests consisting of conceptual questions which can be deceptively simple but are often far more profound than the formally more difficult mathematical problems. She has taught us the difference between knowing and understanding, and that asking a question is often more difficult and important than answering one. In her own way, for the past few decades she has been developing ideas about high school physics education which parallel the modern world trends in improving physics teaching at the university level, and many of her methods are akin to those championed by Dave Pritchard at MIT or Eric Mazur at Harvard.

Nataša's work from her own prospective

According to Nataša, everything she teaches first has to be crystal clear to her personally, before she can adapt and transfer the knowledge to the students at the level which is acceptable and understandable to them. This requires constant learning, thinking, and research. She never relies on a single textbook for her courses, even if she wrote it herself, and she always tries to refresh her lectures with new and innovative examples. She says that the Russian "Quantum" has been one of the most reliable sources of intriguing problems. She is also quick to modestly say that she owes a significant part of her knowledge to her students; she sees every clever question they raise as a sign that her explanations are incomplete, still not sufficiently clear, or maybe even wrong.

Nataša is encouraging and inspiring to all her students, and values both their intellectual abilities and their efforts to learn and to perform experiments. She examines students through longer written exams (four times a year), shorter multiple-choice tests, and oral exams. The written exams test students' ability to apply physical laws to solving problems of various levels of mathematical difficulty. Choosing the correct answers on the multiple-choice tests requires quick thinking and internalization of the key formulae and physical concepts such as conservation laws. In oral exams students show the ability to clearly present and explain topics from the curriculum. In assigning grades, Nataša appreciates students' imagination, creativity and independent work. Participation and success in the national and international competitions, good seminar papers, raising good questions in class, and spotting non-trivial mistakes in her lectures or other students' answers also contribute to the final grade.

Chuck Norris is afraid of Nataša Čaluković

Nataša is not only an excellent teacher, but also an amazing person, and is held in highest regard both by her students and by other physics teachers in Serbia. Her colleagues admire her success with students and like to use the textbooks she wrote. Many ask her to sign their copies of her books. From her side, she greatly appreciates the collaboration with her colleague Jovica Milosavljević because of his efforts to build and maintain an excellent Physics laboratory in their school. Her great authority among the students relies on her knowledge and years of experience, but also on the fact that she treats all students equally and expects them to learn a lot. She is intellectually extremely strict, but always fair. As the saying among the current students of the Mathematical High School goes, Chuck Norris is afraid of Nataša Čaluković. To a lesser teacher that would have been enough of an accomplishment, but she keeps striving for more. ■

Facts and figures

Nataša Čaluković is an exceptional educator. Since 1986, 26 of her students made 36 appearances at the International Physics Olympiads and Junior Science Olympiads. They were honoured by two gold, nine silver, and twelve bronze medals, as well as ten honourable mentions. During her carrier she motivated more than 65 of her pupils to choose the career of a physicist. Her former students are now researchers or faculty members at several Institutes and Universities in Belgrade (>10), in Austria, UK, USA, The Netherlands and Germany.

The Mathematical High School is by far the most respected secondary school in Serbia and one of the best educational institutions in the region. In the forty four year long history of the school its students have won more than 300 medals at the International Mathematical, Physics, Computer Science and Astronomy Olympiads. The school has long standing collaborations with similar institutions worldwide as well as with higher education establishments in Belgrade.

About the authors

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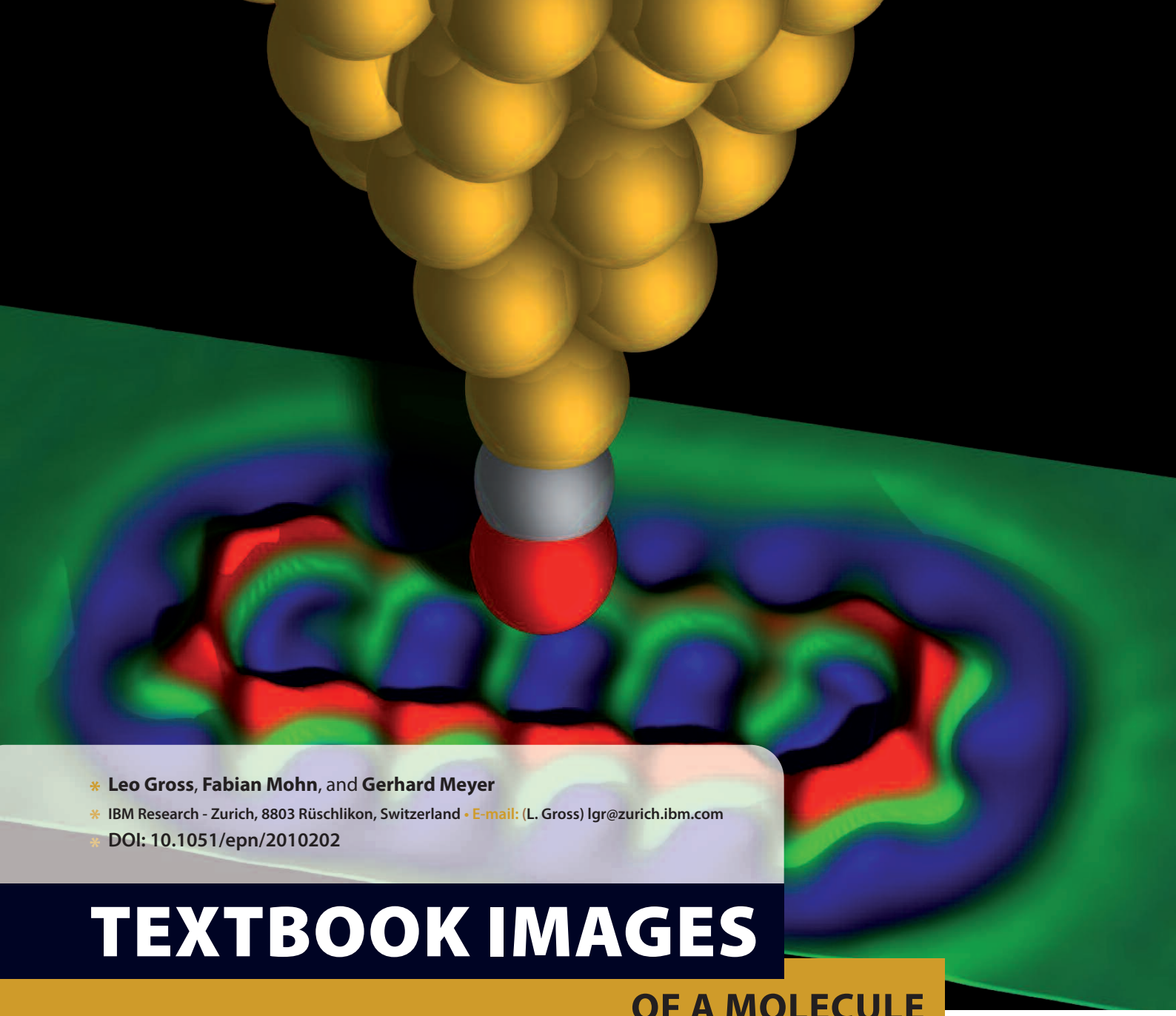

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* DOI: 10.1051/epn/2010202

TEXTBOOK IMAGES OF A MOLECULE

By means of noncontact atomic force microscopy it is possible to atomically resolve individual organic molecules. For this purpose, being able to control the atomic structure of the tip apex is crucial. With a CO-terminated tip, the complete chemical structure of a pentacene molecule could be resolved, showing the five fused hexagonal carbon rings and even the C-H bonds [1].

The ability to resolve the atomic structure of single molecules can enable or facilitate studies of various basic chemical and physical processes such as chemical reactions, charge transfer, conformational changes, and molecular adsorption on the level of individual molecules. Application in the fields of surface catalysis, organic photovoltaics, and future molecular electronic devices will benefit from such investigations.

Scanning probe methods are ideally suited for investigations of individual adsorbates, in contrast to diffraction methods which only yield information for ensembles of atoms or molecules. The scanning probe methods that achieve the highest spatial resolution are scanning tunneling microscopy (STM) and its offspring, atomic force microscopy (AFM). Both methods have been successfully employed in the past to image numerous surfaces with atomic resolution, but the atomic structure of an individual molecule has not been resolved until now. To understand the particular difficulties in the imaging of molecules, it is important to review the working principles of STM and AFM.

▲ **Model of a CO functionalized tip above a pentacene molecule. The measured AFM data (frequency shift obtained in constant height mode) is shown as color coded map.**

STM vs. AFM

In STM, an electrostatic potential U is applied between the tip and the sample and the resulting tunneling current I_t is measured. As a consequence, STM is sensitive to electrons with energies lying between the Fermi energy E_F and $E_F + U$. STM can be used to image molecular frontier orbitals, as has been demonstrated by Repp *et al.* [2], who recorded fascinating images of the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) of a pentacene molecule. This information is of great importance, as it reflects the electronic properties of the molecule. However, the atomic positions that would be revealed by imaging the inner electrons (with energy levels much lower than the Fermi level) are hardly accessible by STM.

The **atomic termination** of the tip is **crucial** for the **contrast** observed above **the molecule.**

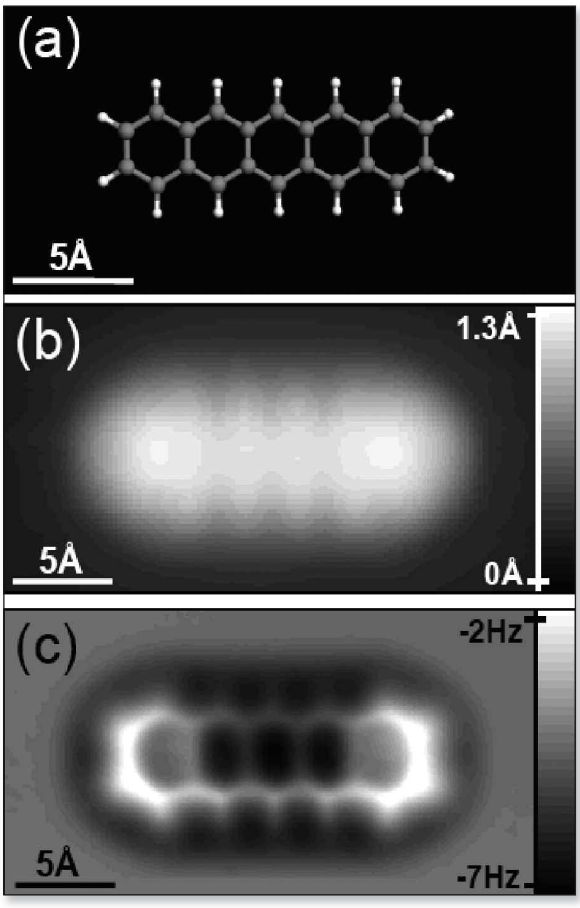
Noncontact AFM (NC-AFM) relies on a completely different imaging mechanism. Here the probe is attached to a mechanical resonator, which is oscillated at its resonant frequency. The imaging signal is given by the frequency shift Δf of the resonance that arises due to forces acting between the tip and the sample. The energy selection of electrons contributing to STM images does not apply to AFM. However, there are several reasons that render AFM investigations on single molecules very challenging. One problem is the strong influence of the exact atomic composition and geometry of the tip. In addition, the attraction between the tip and the molecule can lead to unstable imaging conditions, due to displacement or pick-up of the molecule by the tip. Both problems can be solved by functionalizing the tip apex with different atoms and molecules, as will be shown below.

To achieve atomic resolution with AFM, it is necessary to operate in the short-range regime of forces, where chemical interactions give significant contributions. In this force regime, a cantilever of high stiffness is desirable, to enable operation at small oscillation amplitudes (on the order of 1 Å), as pointed out by Giessibl [3]. In our study, we used a homebuilt combined STM/AFM based on a qPlus sensor design [4] operated in an ultrahigh vacuum at a temperature of 5 K. The high stiffness of the tuning fork [5] sensor allows stable operation at oscillation amplitudes down to 0.2 Å. A metal tip was mounted on the free prong of the tuning fork, with a separate tip wire attached to measure the tunneling current.

Pentacene imaging

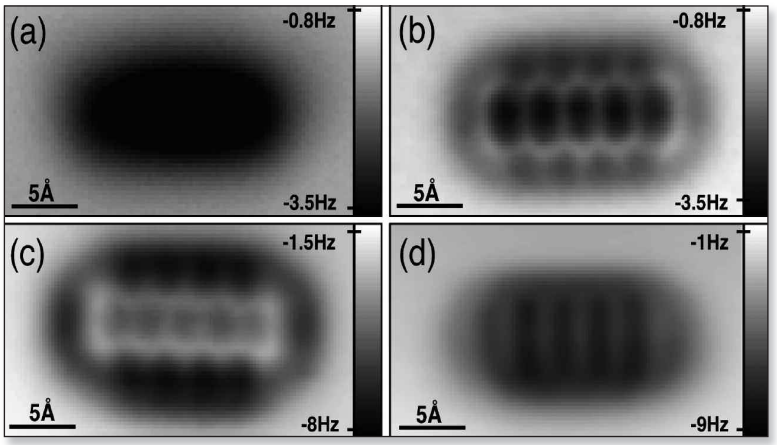
The object of our study is pentacene ($C_{22}H_{14}$, see Fig. 1a), a linear polycyclic hydrocarbon consisting of five fused benzene rings. We imaged pentacene molecules in STM (Fig. 1b) and AFM mode (Fig. 1c) on Cu(111) after a CO molecule had been picked up deliberately with the tip. The CO tip termination led to a striking enhancement of the lateral resolution in the AFM mode. The CO molecule is known to be adsorbed with the carbon atom toward the metal tip and is known to affect STM imaging as well [6]. Several faint maxima and minima are visible in the STM image because of the interaction of the CO with the pentacene orbitals. In the AFM image (Fig. 1c) the five hexagonal phenyl rings of each pentacene molecule are clearly resolved. We observe local maxima of Δf above the edges of the hexagons, near the carbon atom positions, and minima above the centers of the carbon rings (hollow sites). These observations are in concordance with recent AFM measurements on single-walled carbon nanotubes [7]. We also observe the carbon-carbon bonds in the AFM images and even the carbon-hydrogen bonds, indicating the positions of the hydrogen atoms within the pentacene molecule.

In terms of future applications in molecular electronics, insulating substrates will be very important. To prove that this imaging mechanism can indeed be used on insulators, we carried out additional investigations on an insulating NaCl film of a thickness of two monolayers (ML) on a Cu(111) substrate (Fig. 2). Moreover, measurements with different atomic tip terminations were performed to study their respective



► **FIG. 1:** STM and AFM imaging of pentacene on Cu(111). (a) Ball-and-stick model of the pentacene molecule. (b) Constant-current STM measurement (CO-terminated tip, I_t = 110 pA, V = 170 mV). (c) Constant-height AFM measurement (CO terminated tip, tip height z = –0.1 Å with respect to the STM set point above Cu(111), oscillation amplitude A = 0.2 Å).

effect on the AFM contrast. Using specific protocols to pick up different known adsorbates with the tip apex, we created tips terminated with Ag, CO, Cl, and pentacene, and imaged pentacene molecules with these tips as shown in Fig. 2. For each tip, the tip height z was minimized to the closest distance that would still allow stable imaging. Comparing the different tips, we see that the atomic termination is crucial for the contrast observed above the molecule. It should be noted that with metal-terminated tips (Ag, Au, or Cu), we never observed any atomic contrast, probably because the molecule was always picked up by the tip from the surface before the regime of short-range chemical forces was reached. The highest lateral resolution was observed with CO-modified tips, and in the following we concentrate on this specific tip termination.



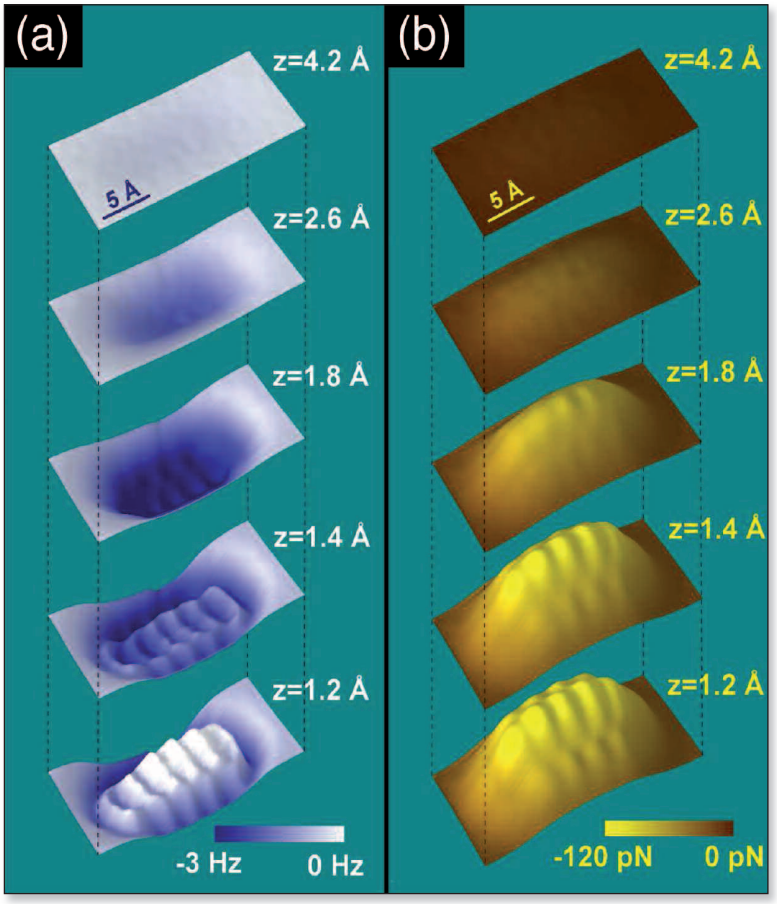
▲ **FIG. 2:** Constant-height AFM images of pentacene/NaCl(2ML)/Cu(111) using different tip modifications. (a) Ag tip, $z = -0.7$ Å, $A = 0.6$ Å; (b) CO tip, $z = +1.3$ Å, $A = 0.7$ Å; (c) Cl tip, $z = -1.0$ Å, $A = 0.7$ Å, and (d) pentacene tip, $z = +0.6$ Å, $A = 0.5$ Å. The z-values are given with respect to the STM set point ($I_t = 2$ pA, $V = 200$ mV) above the NaCl(2 ML)/Cu(111) substrate.

Decomposition of forces

Our AFM measurements yield more than an image of the molecular structure – the actual intermolecular forces can be extracted. AFM can directly quantify forces and energies in processes on the atomic scale. For example, recently the force needed to laterally move a single adatom and the corresponding diffusion barriers have been determined [8], and even the magnetic exchange force was measured with atomic resolution [9]. To extract the force, one needs to integrate Δf over z, because the measurement value Δf is basically proportional to the derivative of the force, with some corrections for the finite value of the oscillation amplitude [10]. Therefore in the experiment, Δf has to be recorded as a function of the distance, starting far away (several Å) from the surface. We recorded this data in a 3D field above a pentacene molecule. Figure 3 shows Δf and the extracted forces for different tip-sample distances. We observe a featureless molecular image for large distances ($z > 2.8$ Å). With decreasing tip height the contrast increases until we finally observe features on the atomic scale.

Before we try to explain the contrast formation, we want to separate the force contributions between the sample and the CO molecule on the one hand, and between the sample and the rest of the tip on the other. This separation was done experimentally, as shown in Fig. 4. We first measured the force acting on a purely metallic tip (Fig. 4a), then picked up a CO molecule with this tip and measured the force again under otherwise identical conditions (Fig. 4b). The difference of the forces for identical tip positions yielded the estimated contribution from the CO molecule only (Fig. 4c). Interestingly, we observe that the CO contribution to the force predominates in the relevant regime, whereas the metallic part of the tip contributes only about 30% to the attractive forces and yields no corrugation on the atomic scale.

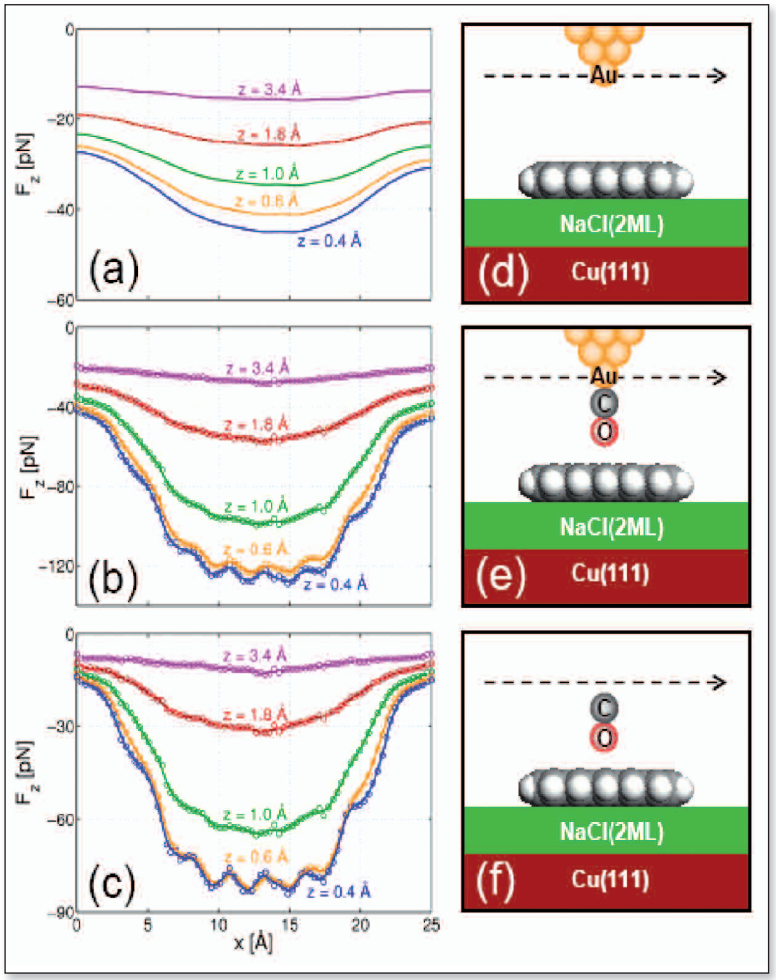
▼ **FIG. 3:** Maps of measured frequency shift Δf (a) and extracted vertical force F_z (b) at different tip heights z. The data shown is part of a complete 3D force field that has been measured in a box of 25 Å by 12.5 Å by 13 Å above a pentacene molecule. The z-values are given with respect to the STM set point ($I_t = 2$ pA, $V = 200$ mV) above the NaCl(2 ML)/Cu(111) substrate.



Contrast formation

A comparison of the extracted forces between the CO molecule and the pentacene molecule with density functional theory (DFT) calculations yielded a good qualitative and even quantitative agreement [1]. In the calculations we can distinguish forces of three different

physical origins: electrostatic forces, van der Waals (vdW) forces, and Pauli repulsive forces. We found that the vdW and electrostatic forces yield a diffuse attractive potential above the entire molecule but show little lateral corrugation on the atomic scale. These contributions give rise to the dark halo surrounding the molecules in the Δf maps. The origin of the atomic contrast is the Pauli repulsion force which becomes significant only when regions of high electron density overlap. These regions are concentrated at the bonds and near the atomic positions and we probe them for sufficiently small tip-sample distances. The AFM image is closely related to the overall electron density, complementary to the STM image, in which the electron orbitals near the Fermi energy are reproduced. Modifying the tip with suitable atomic/molecular terminations was required to operate noncontact AFM in the regime of Pauli repulsion while maintaining stable imaging conditions.



▲ **FIG. 4:** Forces above the long axis of a pentacene molecule. (a) Measured with an Au tip and (b) measured with the same tip after picking up a CO molecule. The *z*-values for both measurements correspond to the same STM-determined set point (I_t = 2 pA, V = 200 mV for the CO tip above NaCl(2ML)/Cu(111)). (c) Difference signal: Forces acting on the CO-terminated tip (b) minus the forces of the tip without the CO molecule (a). The sketches in (d) and (e) depict the measurement geometry of (a) and (b), respectively. (f) Sketch corresponding to the force contribution plotted in (c), *i.e.* the forces acting on the CO molecule only.

Outlook

In this work, we successfully employed NC-AFM to image the chemical structure of a molecule revealing the intramolecular bonds and even the hydrogen positions. Going a step further, it may also be possible to extract details about intermolecular bonds, *e.g.* bond order and length and eventually to probe the reactivity of different molecular sites with respect to the known molecule or atom at the tip apex. Moreover, chemical sensitivity – which was recently demonstrated on semiconductor surfaces [11] – is a goal for future investigations on individual molecules. Furthermore, we aim to combine NC-AFM with electrostatic force microscopy at the atomic level [12] to investigate single-electron transport and charge distributions in metal-molecule systems. ■

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THE QUEST FOR VERY HIGH EFFICIENCY IN PHOTOVOLTAIC ENERGY CONVERSION

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Photovoltaic conversion of solar energy could be much more effective than it is currently, using basic P-N junctions. The approaches to reach the conversion limits (~90%) are very challenging. Some have already been demonstrated (multi-junctions). Others, with the description of excited states in condensed matter and nanosciences having improved considerably, are only waiting for bold scientists…

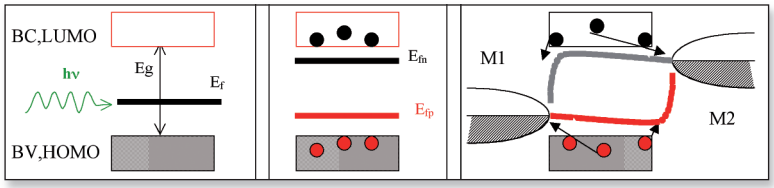
▲ Solar panels, ©iStockPhoto

Like any conversion system of energy, a photovoltaic generator has its performances limited by the laws of thermodynamics. In a first approach, one can regard the sun as a hot source with T = 6000 K, the cold source being the environment (T_e ~ 300 K). The Carnot efficiency of the solar energy conversion is 95 % in theory! However, today's best photovoltaic devices, semiconductor photodiodes, achieve efficiencies of only 20-25 %. The difficulty lies with the optimal conversion of a whole range of photons whose energy goes from the infrared to the ultraviolet, with only one active material whose optical properties can be optimally adapted only to a given photon energy (the absorption threshold, or energy gap, E_g). To understand why, we must return to the principles of photovoltaic conversion [1], such as the devices currently used.

This conversion is done in three stages (fig. 1): (a) absorption of photons of energy $h\nu > E_g$, which creates populations of electrons and holes out of equilibrium; (b) each type of carriers very quickly reaches steady state defined by a quasi-Fermi level E_{fn} for the electrons and E_{fp} for the holes, whose difference, $E_{fn} - E_{fp} = qV$, is the recoverable free energy from photon absorption (V is the photovoltage); (c) the carriers, collected by the contacts before they can recombine, participate in the photocurrent.

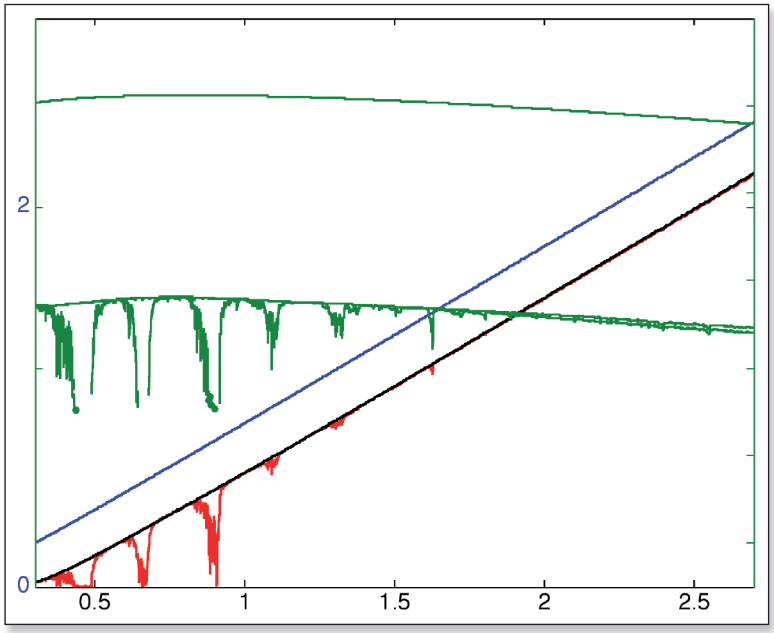
Photovoltaic devices are rather similar to an electrochemical battery: only their anode and their cathode consist of different energy levels from the same material. In this device, one must have $h\nu > E_g$ because of the properties of absorption, but also $E_g > E_{fn}$-E_{fp}[1]. The fraction of energy which can effectively be converted by an absorbed photon, qV/hν, is therefore much smaller than its maximum value, because the free energy obtained from each photon is independent of its energy (the remainder goes to the atomic lattice heat in less than a few picoseconds, during the carriers thermalisation). Including that part of the photons that is not absorbed, the efficiency is limited to 30 % for the optimal gap E_g and under standard conditions of illumination [1]. Since the quasi-Fermi levels depend on the charge carriers concentration[2], which in turn depends on the light flux, it follows that the recoverable free energy per incident photon increases with their flux: it is advantageous to concentrate the solar flux before conversion. The potential efficiency gain is 3 percentage points per decade.

Note that the maximum concentration of solar flow is limited to a factor of 42 600[3] by thermodynamics: the image of an object cannot be hotter than the object itself[4]. One can calculate the maximum value of free energy which can be extracted for each absorbed photon (fig. 2), independently of the conversion system [2]. This free energy depends solely on the energy of the photon and the incident flux. With the help of figure 2, one calculates that the maximum efficiency of a photovoltaic device is 67 % under standard solar illumination and 87 % under maximum concentration. If no such efficiencies could have been approached yet, it is because the materials and technologies were not ready to meet the severe specifications necessary.



▲ **FIG. 1: Principle of photovoltaic conversion, broken up into three principal stages. (a) Absorption of a photon and promotion of an electron to a higher and empty level. (b) Establishment of two populations of electrons and holes in internal quasi-equilibrium (via fast, ps, relaxation processes), but unbalanced with one another (the interband relaxation processes have a typically ns characteristic time τ_n). (c) Preferential collection of a type of charge carrier to each contact after a time of transit τ_D. M1 and M2 are the two contacts, here pictured as metallic, for the holes and the electrons, respectively. BC is the bottom of conduction band, BV is the top of valence band, LUMO is the lowest unoccupied molecular orbital, HOMO is the highest occupied molecular orbital; they play a similar role in solids and molecules, respectively.**

▼ **FIG. 2: Recoverable optimal free energy μ by an absorbed photon, *i.e.*, at the maximum electric power extraction (ordinate, left axis), according to both the photon energy (abscissa axis) and the incident photon flux (different curves). The blue curve corresponds to a 6000 K black body spectrum, the red curve to the terrestrial solar intensity, and the black curve with that of solar flux above the atmosphere. Green curves: the photons fluxes on a log scale (right axis) for the same spectra.**



Very high-efficiency pathways

The possible strategies are along three main directions, all having ultimately conversion efficiencies close to 85 %.

1. *The 'photonic' devices:* if all solar energy were concentrated in a narrow spectral band, the current devices would already be able to convert somewhat over 50%. One can thus try to adapt the incident spectrum to one or more photodiodes. The new requirements translate into optical properties of materials.
2. *Optimised absorption materials:* materials having intermediate electronic levels serving as "scale for electrons" or materials allowing the generation of several electron-hole pairs by sufficiently energetic photons . These requirements involve the electronic structure of materials.
3. *Heat engines* in which the absorption of light leads to the production of heat that can still be converted into electric output. In this last case, one needs to look closely at the thermal and "phononic" properties of the solids considered.

I- Photonic devices

Here, the difficult task is either to sort photons to be sent to junctions adapted to the corresponding part of the spectrum (multi-junctions), or to change their energy so as to lead to a "bunched" distribution, before being recovered each time by a standard diode adapted to this narrowed spectrum.

a. Multi-junctions

notes

[1] When E_{fn}-E_{fp} becomes close to E_g, one reaches population inversion between electrons and holes, and stimulated emission of radiation opposes a further increase in qV.

[2] In most cases, $E_f = E_f° + kT.log[n]$, where n is the concentration of electrons of the group of energy levels in (quasi-) equilibrium and $E_f°$ the free energy of the standard state, similar to that of the chemical potential of a perfect gas.

[3] The maximum concentration factor is 4π divided by the solid angle of the sun, *i.e.*, when the cell can only see the sun. At higher concentration factors, the focal point would have a higher radiation temperature than the source, which is thermodynamically impossible.

[4] If not, one could reversibly transport heat of a cold body towards a hot body, and we would have a perpetual motion machine.

In a traditional device, the photons whose energy conversion is most effective are those whose energy is just above the threshold of absorption (energy gap E_g). For those, outputs of about 60 % are reached in experiments, rather close to expectations (fig. 2). The use of several different cells materials, each one with a gap optimised for a different part of the solar spectrum, makes it possible to increase the output (see box). For a given number of cells and an incident spectrum, there is a best choice for the gaps giving the highest output [2]: for example, for three cells under maximum concentration, the maximum theoretical yield is 63 % (49 % without concentration). These devices exist, and achieve outputs of ~43 % (under concentration) [3]. They involve very advanced fabrication technology, but represent the first actual devices with very high efficiency potential. The highest efficiencies were obtained with structures based on stacks of epitaxial III-V compounds. Yet, it has to be realized that the incremental gain in power from the addition of a cell in a stack including N junctions, varies like $1/N^2$. If one takes into account the induced losses (electrical and optical), the expected net gain from another cell is close to zero after the 4th cell.

b. Optical converters

Alternatively, one could change the wavelength of the photons before they reach the photodiode, to obtain a narrower spectrum. In the approach 'photon addition', the photons whose energy is too weak to be used directly by a photodiode could be converted by nonlinear optics into a lower number of photons of larger energy. The main results on this topic have been obtained with materials in which infrared radiation is absorbed by several ions of a rare earth and its energy transferred to another lanthanide, able to emit effectively at close to double frequency [4]. So far, approximately 16 % of the absorbed photon energy in the infrared was actually converted into photons of twice the energy.

Another principle, 'photon cutting' consists in absorbing photons of high energy in a luminescent converter to emit several photons of lower energy, to increase the current output of the photodiode. Fluorescent converters such as YF_3:Pr or $LiGdF_4$:Eu have been proposed but are only efficient with UV light.

II- Optimized absorption mechanisms

a. Intermediate levels devices

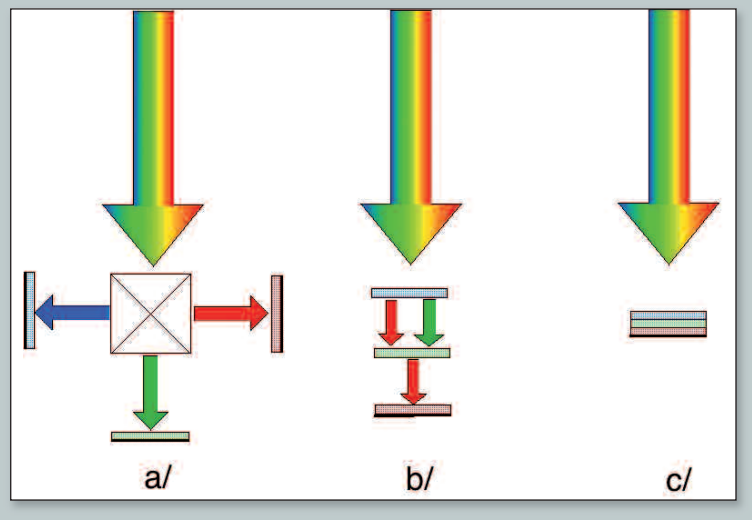
In addition to the transitions from the valence band to the conduction band, which take place in the semiconductors under the effect of irradiation, semiconductors can absorb photons of even lower energy via intermediate levels located in the forbidden band, which play the role of a 'ladder for electrons' (fig. 3 b) [5]. Such a device would be similar to a multi-junction with respect to efficiency, but with the simplicity of a simple junction. The main issue is achieving a strong absorption of the intermediate levels without excessively increasing the rate of non-radiative recombination. There are many ways of obtaining intermediate levels or bands like, for example, by the introduction of extended defects or impurities, or of a superlattice of quantum dots. Other intermediate level systems have appeared more recently: ferromagnetic semiconductor compounds, of the type of GaAs:Mn, could present reduced non-radiative decay , because of the selection rules on the spin which could slow down some recombination processes [6].

b. 'Scintillators' materials

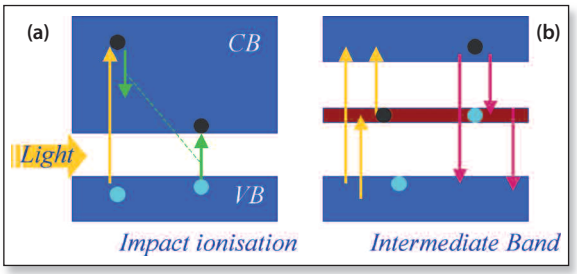
The absorption of photons having energy more than twice that of the gap makes it possible to consider other mechanisms, where the excess energy can be used to create a second electron-hole pair. This phenomenon is called 'impact ionisation' (fig. 3a). The outputs of devices with impact ionisation can have practical interest, provided that the process is effective in the vicinity of the physical threshold (~ 2 E_g). Work at the Max Planck Institute of Stuttgart predicted that the alloys Si-Ge could show a measurable effect. But this was found to be lower

Principle of multi-spectral conversion (triple junction)

a) An optical device separates sunlight by means of filters in three beams "blue", "green" and "red", which are converted by three cells whose band gaps were adapted for these three spectral bands. One can simplify the device as indicated in b) noticing that the "blue" cell does not absorb the wavelengths higher than its threshold of absorption. It can thus be used as filter for "green" and "red" cells. In the same way, the "green" cell lets the "red" beam pass. It is necessary, of course, that the substrates of the first two cells are transparent. Finally, in c) a transparent electrical contact between the cells is realized.



One can achieve this stack by deposition of the various cells on the same substrate. To avoid creation of a reverse diode at the interface between two cells (a diode p-n if diodes n-p are piled up), one connects them by a tunnel junction. In case c) the cells are connected in series, whereas in the cases a) or b) one remains free to use the electricity produced in the most effective way.



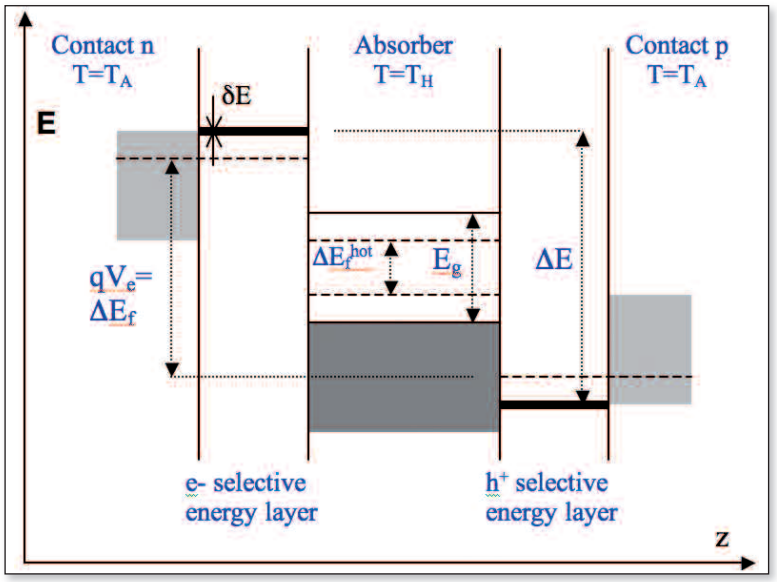
▲ **FIG. 3:** Energy band diagram showing potentially improved carrier compared to the standard case. (a) Impact ionisation enables transfer excess of energy from a carrier to an electron which becomes promoted from the valence band (VB) to the conduction band (CB). (b) An intermediate band allows a better absorption of the solar spectrum. The processes of generation are in yellow and those of recombination are pink.

than 1 % of the output power of cells made of this material. High values of impact ionization have so far been observed only for energies of photons higher than 3 E_g [7].

III- 'Heat engines': hot-carriers solar cells

The carriers generated in the absorber are not thermalised instantaneously with the network at temperature T_A, but form in a transitory way a hot gas of electrons and holes: their distribution corresponds to a temperature $T_H > T_A$. If these carriers can be collected quickly via selective energy levels (fig. 4), the heat flow through the contacts is minimal and the kinetic energy conversion of hot gas into electrical potential energy is optimal [8]. Calculations of the limit of output give values very close to those obtained with a multi-junction device containing an infinite number of cells, each one adapted to a fraction of the spectrum, and this for a system of a much simpler concept. It thus acts, to some extent, as the ultimate device of solar transformation energy. No cell with hot carriers was built yet. However, experiments showed that hot carriers thermalisation rates can be reduced under strong excitation in nanostructures to the point that conversion efficiencies above 50 % under concentration are possible [9]. These outputs are sensitive to the energy width of the contacts beyond some meV, because the latter introduce a thermal loss by transfer of heat. But more than decreasing the thermalisation rate, the practical realization of selective contacts is likely to be the delicate point in the fabrication of these devices.

▼ **FIG. 4:** Energy band diagram of a hot-carriers cell. The solar photons are absorbed in the central part where a gas of hot electrons is formed. The internal free energy available (at T_H) is ΔE_f^{hot}. Their excess of kinetic energy enables them to be collected at an energy higher than that of the edge of the conduction band (for the electrons) or valence band (for the holes): the energy per pair ΔE can be significantly larger than E_g. The selectivity in energy (given by δE, the energy width) of the contact is enabling minimal heat transfer of hot carriers to the contacts.



Conclusion

Will we find systems radically different from diodes for high performance photovoltaic conversion? There are in any case a great number of possibilities to achieve that. In the short run, multi-junction devices should demonstrate significant progress. They may even have a significant impact on the production of photovoltaic electricity, by using solar tracking and concentration, on a somewhat longer term. Finally, later on, cells with intermediate levels or hot carriers, which raise the greatest scientific and technological challenges, could enable us to approach the ultimate performances. Thanks to the discovery of new materials resulting, for instance, from nanotechnologies, this possibility is getting closer every day. ■

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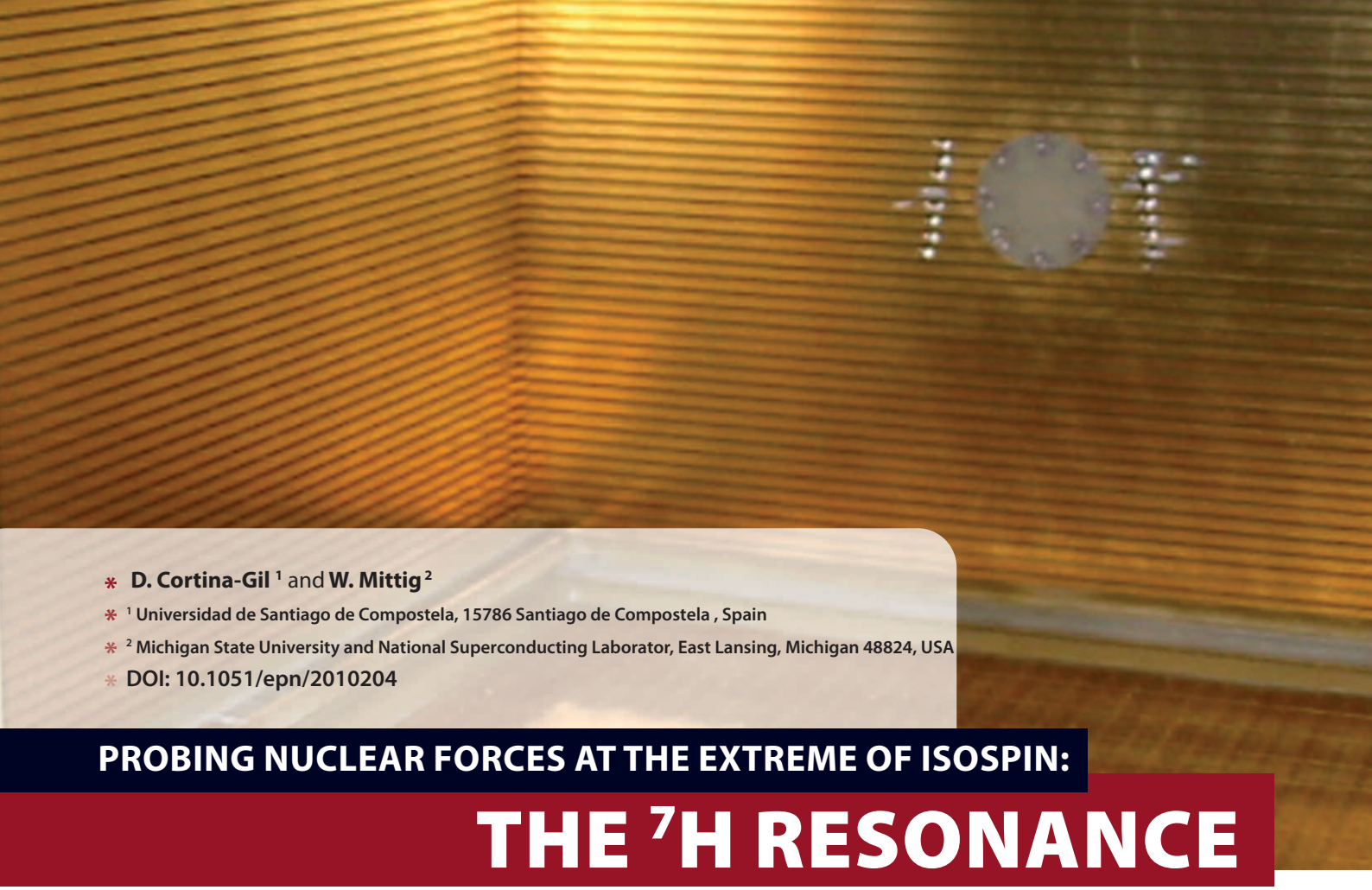

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PROBING NUCLEAR FORCES AT THE EXTREME OF ISOSPIN: THE ^{7}H RESONANCE

Modern high-intensity accelerators provide access to new regions of the nuclear chart. This allows one to study the properties of extremely weakly bound or even unbound nuclei which spontaneously emit protons or neutrons. These "exotic" nuclei have a huge imbalance in the proton/neutron ratio, adding a new degree of freedom - the isospin - and opening a large field of new experimental possibilities.

▲ An inner view of the MAYA detector

It has been observed that, in these systems, nuclear forces manifest themselves in different ways. This is interpreted presently as an isospin dependence, and is questioning our understanding of the behaviour of nuclear matter going from proton- rich to neutron-rich matter.

The description of nuclear forces in these weakly bound nuclear systems represents an enormous challenge. The interaction between nucleons is responsible for the creation of particular structures. The study of these structures, at the limit of nuclear binding and beyond, where non-perturbative phenomena become important, is a unique source of information. "Ab initio" calculations illustrate nicely these non-perturbative phenomena. These calculations start from interactions describing perfectly a large body of nucleon-nucleon scattering data and then solve, without further approximation, the nuclear n-body problem. However, they fail completely in reproducing macroscopic observables as, for example, nuclear binding energies (see figure 1) [1]. These large discrepancies are attributed to the importance of 3-body forces: the interaction between two nucleons is modified by the presence of a third nucleon.

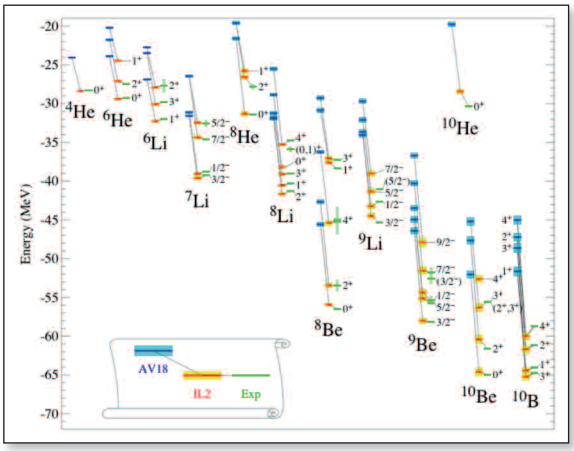
Non-perturbative phenomena in nuclear physics

We can explain nuclear interaction in terms of virtual pion exchange between two nucleons. This exchange may, for example, result in an excitation of the Δ-resonance [unstable nuclear state defined by a mean energy value (E_R) and a given width (Γ_R), determined by its half-life (dt) due to the relation $\Gamma_R.dt = \hbar$] of one of the nucleons that interacts in this excited state with a 3rd nucleon present in the nuclei. This last interaction can be seen as a higher order correction of the original interaction of the first two nucleons. The importance of this higher order correction is not due to the strength associated with the interaction but to its intrinsic nature. Properties of very strong Coulomb interaction have been tested in the Mott-scattering of Pb+Pb [2]. The Coulomb potential energy in this system is of the order of 500 MeV, one order of magnitude higher than the binding energy of the systems of figure 1. However, in this particular case higher order corrections, such as vacuum polarization, are only of the order of 10^{-4}. So in the case of the nuclear interaction, the origin of the

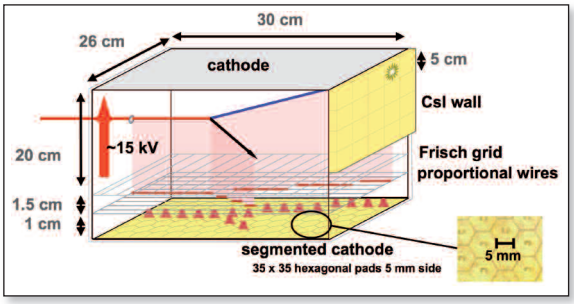
strong effect of higher order corrections cannot be attributed to the interaction strength, but is due to the fact that it involves the strong interaction that has intrinsically non-perturbative aspects.

The coupling to continuum in loosely bound or unbound systems becomes so important that it cannot be treated as a perturbation. Examples of a non-perturbative treatment have been achieved in recent shell-model calculations [3].

We focus now on another example of non-perturbative systems: the creation of very asymmetric nuclear matter and, particularly, on the observation of the extremely neutron-rich hydrogen isotope ^{7}H, that emits spontaneously 4 neutrons leading to a triton (^{3}H). The search and characterization of Hydrogen resonances is one of the stringent tests about nuclear formation. Recent theoretical predictions [4] along with experimental indications [5] predict that ^{7}H with six neutrons and a single proton will be the heaviest possible hydrogen system and will also constitute the most exotic nuclear system ever synthesized with a N/Z=6.



▲ FIG. 1: Comparison of experimental binding energies (green) for lower quantum states of light nuclear systems A=4-10 with those predicted by Greens function Monte Carlo GFMC method [1]. These predictions are built first using a realistic two-body interaction, the Argonne V18 (AV18) potential (blue), and then the Illinois-2 (IL2) three-nucleon potentia l(red).The use of three-nucleon potential improves notably the result, suggesting the importance of using a more and more complete description of the nuclear force. Thin black lines are used to connect predictions and experimental values for each state. Credits for the figure to S.C Pieper, R. Wiringa and J.Carlson.



▼ FIG. 2: The active target MAYA with its different components: active volume and amplification/detection zone. This picture illustrates a typical example of a binary reaction in the gas target. The secondary beam (red horizontal line) enters into the gas cell producing a binary reaction (vertex). This results in a fragment (black line) that is stopped inside the gas volume and a light charge fragment (blue line) with higher energy that escapes and is further identified in an ancillary detector (CsI scintillation crystal wall).

Study of very exotic nuclear systems

The synthesis and study of exotic nuclear systems require the use of radioactive beam facilities that provide beams of unstable nuclei, not existing on earth, from intense stable beams. The Isotope Separation On Line (ISOL) method is used for the production of low-energy unstable beams. The primary stable beam impinges on a thick target where the radioactive species are created. They need to be extracted and accelerated up to energies suitable for studying nuclear reactions around the Coulomb barrier and higher.

The relatively low intensities of the exotic beam produced, together with the extremely low cross-sections of the reactions involved make the experimentation with these exotic nuclei very challenging. Fortunately, the sensitivity of the detectors and of the experimental methods used has impressively increased in the last years allowing nowadays detailed spectroscopic studies with beam intensities down to the order of 1 particle/s compared with values of 5.10^{9} particles/s that were necessary two decades ago.

The use of detection systems with the highest possible efficiency is essential. Another option is the increase of the target thickness, but this dramatically reduces the energy resolution achieved and compromises the information obtained

An elegant solution is found in the use of active targets: gaseous detectors where the filling gas plays the dual role of detection gas and target. They compensate for the low rates associated with exotic nuclei by achieving a large detection efficiency, which can nominally reach 100%. Further, they can determine the interaction point between projectile and target nuclei on an event-by-event basis, allowing the gas target thickness to be increased without degrading the energy resolution. Moreover, the detection of recoils inside the active target reduces the detection threshold to a minimum, and thus guarantees detection even for very low recoil energies.

This new approach has been used in the experimental study of the ^{7}H system [6], performed at GANIL (France), where a secondary beam of ^{8}He with an energy of 15.4 MeV per nucleon was produced in the Spiral facility by the Isotope Separation On Line (ISOL) technique [8].

The experimental detection setup consisted mainly of the active target MAYA [9] depicted in figure 2, working essentially like an ionization chamber. The MAYA detector is divided into two working zones. The ionisation zone (upper part) consists of an active volume (26×20×30 cm^{3}) filled with isobutane C_4H_{10}. The amplification/detection

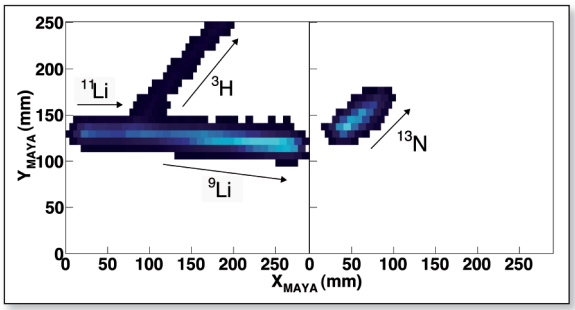
zone (lower part) contains a wire plane and a cathode plane segmented in 35×35 hexagonal pads (5 mm side). The ^{7}H system was produced by the one-proton transfer reaction of the ^{8}He beam with the carbon atoms in the isobutane, ^{8}He +^{12}C→^{7}H +^{13}N. Beam particles and charged reaction products ionize the isobutane along their paths in the gas. The electrons released in the ionization process drift toward the amplification zone, where they are multiplied around the wires inducing a mirror charge in the pads of the segmented cathode. The determination of the drift time and of the charge collected on the pads provides, in principle, the 3-D reconstruction of the trajectories of the secondary beam (^{8}He) and of the reaction products (^{7}H and ^{13}N). Figure 3 presents typical examples of trajectory imaging with MAYA. In figure 3 (left panel), the image of the study of the binary ^{11}Li+p→^{9}Li+t reaction [10] is shown. In this case we can identify clearly the trajectory of the exotic-projectile (^{11}Li) and both reaction products (^{9}Li and triton).

Figure 3 (right panel) depicts the ^{8}He +^{12}C→ ^{7}H +^{13}N reaction, where only ^{13}N is registered in the active target volume. The ^{7}H identification is more complex due to its unstable nature. The scattered ^{7}H decays very rapidly, before being detected, into triton and four neutrons (^{7}H→t+4n). The experimental setup was not equipped for the detection of neutrons, thus the reaction channel is determined by detecting the remaining charged particles, triton and nitrogen, that could not be simultaneously stopped within the MAYA active volume.due to their very different kinematical properties.

The gas pressure was thus adjusted to stop ^{13}N, and secondary beam particles ^{8}He and tritons, with too low energy-loss in the active volume, could not be traced. Tritons escaped the active volume and were detected by a segmented wall of CsI crystals covering the exit face of MAYA(see figure 2).

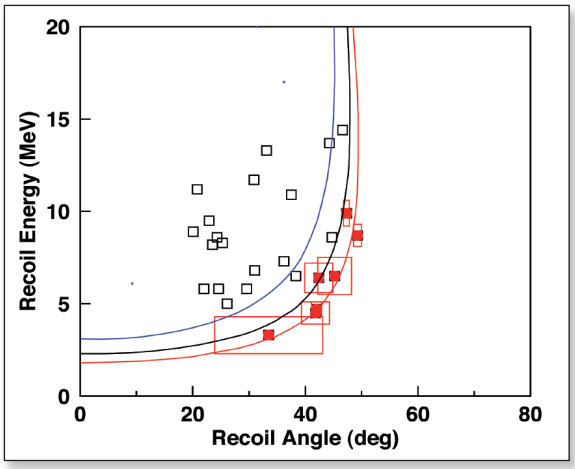
The charge image induced by the recoil nitrogen isotopes was projected in the segmented cathode, where the charge was collected and the range and the total charge determined. The coincident detection of triton and nitrogen restricted the selection to such a binary process and discards contamination from other reaction channels. The recoil scattering angle was determined too, and together with the 3-D tracking capabilities of MAYA allows the extraction of the complete kinematics of the nitrogen selected.

Our experimental setup did not allow an isotopic separation of the recoiling nitrogen. Different reaction channels leading to triton and a recoiling nitrogen isotope are separated using their different kinematics. The points displayed in figure 4 correspond to different nitrogen isotopes that survive the stringent analysis filters. They originate from a binary reaction and are in coincidence with a triton detected in the CsI(Tl) wall. The experimental data of figure 4 are compared to the



▲ FIG. 3: Example of measured binary reactions with MAYA. X_{MAYA} and Y_{MAYA} axis correspond to the dimensions of the segmented cathode (26x30 cm) and show a projection of the reaction on the cathode plane. **Left:** Illustration of an event corresponding to the ^{11}Li+p→^{9}Li+t reaction [10]). **Right:** Illustration of an event corresponding to the ^{8}He +^{12}C→^{7}H +^{13}N reaction at ~123 MeV [7].

▼ FIG. 4: Kinematics of the different reaction channels ^{8}He+^{12}C→^{7}H+^{13}N red line, ^{8}He+^{12}C→^{6}H+^{14}N black line and ^{8}He+^{12}C→^{5}H+^{15}N blue line, with all the experimental data that pass all the analysis filters. The data points marked in red are associated to ^{13}N and directly connected with the ^{7}H resonance formation. Different size boxes represent the experimental error associated with the ^{13}N energy and angle determination for each particular event. The black data points correspond to heavier N isotopes and are linked to formation of lighter H isotopes.

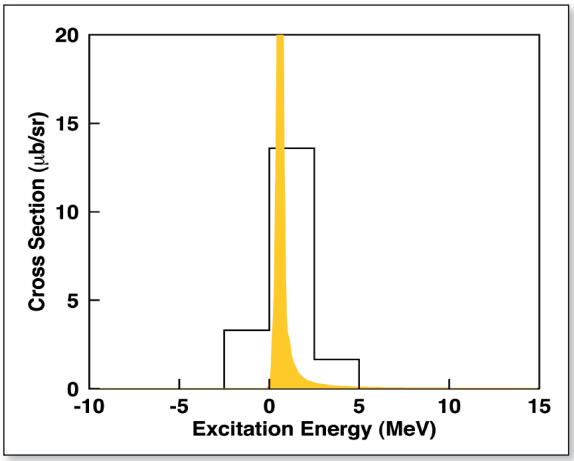


kinematics of ^{7}H formation assuming a rest mass of ^{7}H system equal to the triton and four neutrons (red curve). The same is applied to calculate the kinematics for the ^{6}H (black curve) and ^{5}H (blue curve) formation. Several events (red squares in figure 4) accumulate clearly around the kinematics line corresponding to the production of ^{7}H. The boxes surrounding each event represent experimental errors associated with the determination of the recoil energy and deflecting angle. The ^{7}H resonance energy E_{exc}, defined as the energy above the threshold for the decay of ^{7}H→t+4n, is shown in figure 5 (black histogram). This distribution is normalised by the corresponding measured cross section, which resulted in a ($d\sigma/d\omega$) of 40.1 μ b/sr, with an upper limit fixed by the experimental uncertainty of 98.1 and lower limit of 9.5 μ b/sr . The distribution is then described with a modified Breit-Wigner function, where the cross section depends on the excitation energy through the resonance energy (E_R) and width (Γ).

These parameters are extracted, following a multiparametric Maximum Likelihood fit procedure which is especially suited for low statistical samples. The result is a narrow resonance (yellow function in figure 5) with a width (Γ) of 0.09 MeV (1.03 and 0.03 MeV upper and lower limit) and a resonance energy (E_R) of 0.57 MeV (0.99 and 0.36 upper and lower limit), located just above the threshold of the t+4n sub-system.

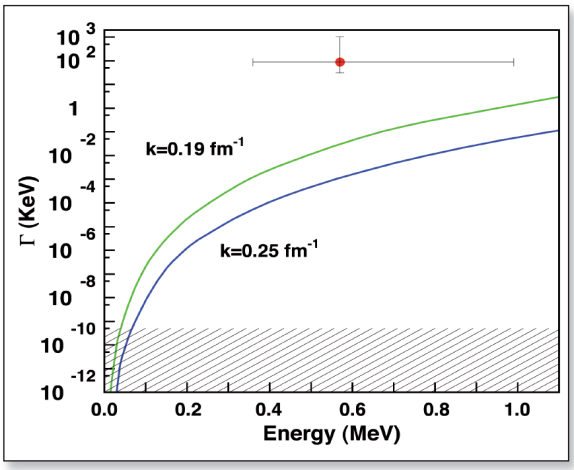
The width of a resonance is directly related to the lifetime of the resonant state. In figure 6, the width expected for uncorrelated four neutron decay as calculated by Golovkov *et al.* [11] is shown for two different parametrisations, together with the experimental value extracted from this analysis. The much larger experimental width implies a correlation of the four neutrons in the emission process. This may be interpreted as a hint for the emission of a neutron cluster, that speculatively may be related to present discussions about the existence of a tetra-neutron state [12]. This effect can be seen as another illustration of the non-pertubative character of such a system near threshold, where special cluster structures may play an important role.

To conclude, the existence of a ^{7}H system formed as a resonance above the threshold of the decay in a multibody system consisting of four neutrons and one triton has been observed and characterized. This was possible only by the use of a new generation high sensitivity active target detector. The non-perturbative description of the decay of such systems is without any doubt a major challenge for present theories. ■



▲ FIG. 5: Energy spectra above the separation threshold of ^{7}H→t+4n normalised to the measured cross-section for the events identified as ^{7}H. The histogram (black solid line) corresponds to the experimental measurement whereas the yellow function is the modified Breit-Wigner function fitted to allow the characterization of the resonance parameters.

▼ FIG. 6: Decay width Γ for the ^{7}H system for an uncorrelated emission of triton and four neutrons evaluated by Golovkov *et al.* [11] using hyperspherical coordinates and for two different values of the k parameter related with the radial part of the interaction (green and blue curves), together with the experimental result.



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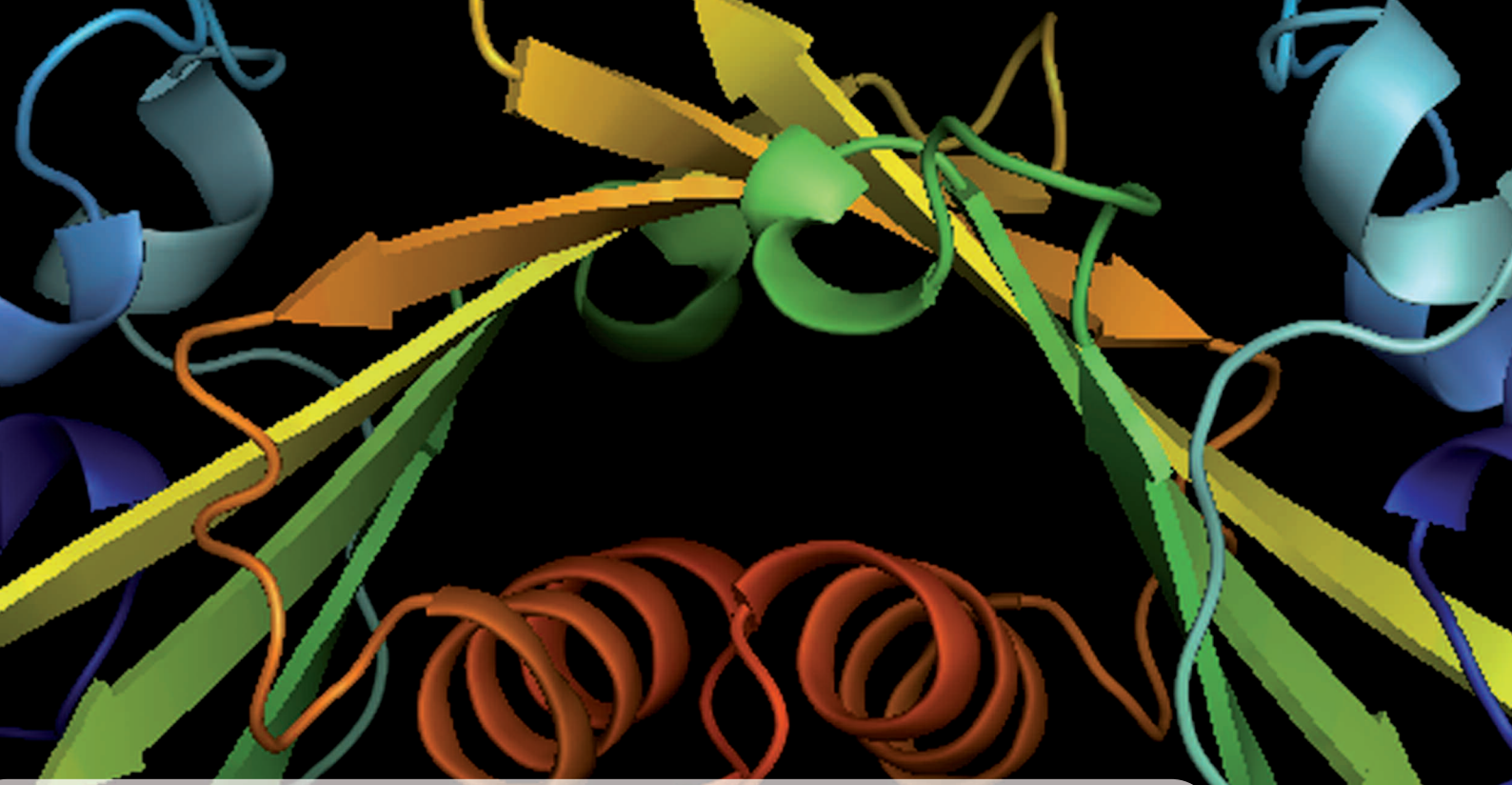

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FLUCTUATION THEOREMS IN SMALL SYSTEMS:

EXTENDING THERMODYNAMICS TO THE NANOSCALE

Recent developments in micro and nanotechnologies enable the manipulation of single molecules one at a time. Such experiments make it possible to resolve energy processes with unprecedented detail at the level of 1 k_BT, the typical energy scale of Brownian fluctuations. Fluctuation theorems establish relations governing energy exchange processes at this level and provide a new methodology to obtain equilibrium information from non-equilibrium experiments.

Biophysics is the branch of science that aims to understand biological processes using concepts and tools from mathematics, physics and chemistry. Molecular biophysics focuses the attention on fundamental processes occurring at the molecular level, like the action of molecular motors [1], the folding of proteins [2], the physical chemistry of nucleic acids [3] or molecular transport through ionic channels [4], among many others. Traditionally, experiments have been done on samples containing a quantity of molecules of the order of the Avogadro number, $\approx 10^{23}$. For example, in calorimetry or nuclear magnetic resonance samples contain trillions of molecules in solution. Thus, measurements are an average over individual behaviours and thermodynamics is the branch of science needed to describe the equilibrium properties observed. Fluctuations often do not play any relevant role as they are too small: their relative magnitude scales as $1/\sqrt{N}$, N being the total number of molecules.

Thanks to recent developments in technology, scientists can investigate the properties of single molecules at high spatial and temporal resolution. Optical tweezers (Box 1), atomic force microscopes, or magnetic tweezers allow us to grab and manipulate one molecule in each experiment and to obtain precious information often inaccessible to bulk methods [5]. Single molecule experiments (SME) make it possible to probe small energies comparable to the energy unit of thermal noise, k_BT (k_B being the Boltzmann constant and T the ambient temperature). To emphasize the smallness of the energy scale, these systems are usually referred to as "small systems". In such conditions, thermal fluctuations

▲ Characteristic 3D structure of the Ivy protein (Inhibitor of vertebrate lysosyme) used by numerous bacteria to be protected from lysosyme. ©CNRS Photothèque C. Abergel lab.: UPR2589 - IGS - marseille

are relevant and deviations from the average behaviour are observable. To be reliable, SME must be repeated several times in order to identify a reproducible pattern in the measurements. Thermodynamics is still applicable, although big relative energy fluctuations are the rule: in such a noisy environment, fluctuation theorems provide a novel conceptual framework useful to characterize a molecule from non-equilibrium SME.

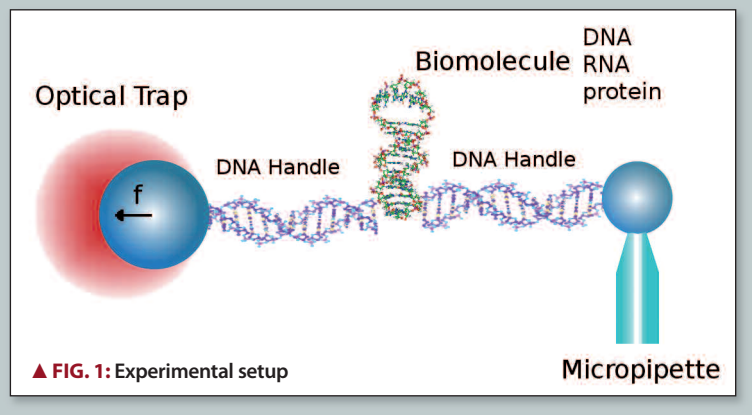
Unzipping experiments

Biomolecules (*e.g.* RNA, DNA or proteins) stretched under force are excellent models to explore the non-equilibrium physics of small systems. The great versatility of DNA synthesis together with its high molecular stability makes it a suitable system to work with. DNA hairpins (fig. 2) are among the simplest DNA structures important in many biological processes. They are formed of a stable DNA double helix (called 'stem') ended by a loop. The number of base pairs in the double helix and the size of the loop are parameters that we can control. This allows us to design DNA molecules with specific thermodynamic and kinetic properties.

Single molecule experiments (SME) make it possible to **probe small energies** comparable to the energy unit of **thermal noise, k_BT**

Optical Tweezers and Single Molecule Experiments

Optical tweezers allow us to manipulate tiny objects with sub-nanometer resolution and to exert mechanical forces in the picoNewton range. By optically trapping micron-sized beads it is possible to grab and pull biomolecules that are a thousand times smaller than the beads [9].
Molecular biology tools are employed to insert a molecule between molecular handles. This complex is then tethered between two micron-sized polystyrene or silica beads.



▲ **FIG. 1:** Experimental setup

One bead is captured in the optical trap, while the other is immobilized by air suction on the tip of a micropipette (see figure). The bead in the optical trap feels a force towards the center of the trap. This force is then transmitted to the molecular system in mechanical equilibrium. Handles act as force transducers and provide free space to avoid spurious interactions between the molecule under study and the beads.

In unzipping experiments [6], a DNA hairpin is converted into a single DNA strand by pulling apart the two chains of the double helix from the same end (see Box). By applying force, weak molecular interactions are disrupted and energies of a few k_BT (or kcal/mol) are probed. Unzipping occurs around 15 pN, which is the force required to overcome the hybridization forces that bind the two complementary strands of the double helix. When unzipping long DNA hairpins (a few hundreds of base pairs) at a constant speed a force-distance curve (FDC) with a sawtooth pattern is observed (fig. 3a) [7]. At each force rip some base pairs are released and the DNA hairpin becomes progressively opened, until it unfolds completely.
In short hairpins (a few tens of base pairs) a single rip is observed revealing a two-states behavior: at low forces the molecule is in its native state, while at high forces the unfolded and stretched state becomes thermodynamically stable (fig. 3b) [8]. The rupture process is thermally activated (stochastic), so the value of the force at which the hairpin unfolds changes at each unzipping experiment under the effect of thermal fluctuations (fig 3c). Once the molecule is in the unfolded state, we can recover the native structure by releasing the force applied to the system. The latter process is called zipping.

Fluctuation Theorems

Fluctuation Theorems (FT) establish fundamental relations about energy exchanges between a non-equilibrium system and its environment, and allow one to obtain equilibrium information from non-equilibrium experiments [10]. SME are an ideal laboratory to explore FT.
To better understand FT let us consider a small system, prepared in an arbitrary initial state and kept in contact with a thermal bath, that is submitted to an external time-dependent perturbation. Any perturbation can be described by a macroscopic coordinate of the system that is reproducibly changed from an initial to a final value following a specified protocol. The work W measured along the path or trajectory will vary from experiment to experiment because we cannot control the microscopic configurations explored by the system under the perturbation (*i.e.*, work is a path-dependent variable). As work is an extensive variable, these fluctuations are suppressed in experiments with a large number of particles. However, in SME work fluctuations are significant because of the small energies involved. For infinitely slow perturbations, the adiabatic hypothesis tells us that the process is reversible and the work is equal to the difference in free energy between the final and initial states, $W_{rev}=\Delta G$.
However, the faster we apply the perturbation, the more the mean work $\langle W \rangle$ increases (averaged over a large number of experiments undergoing the same protocol). Because the free energy remains the same, the average

dissipated work $\langle W_{dis}\rangle=\langle W\rangle-\Delta G$ also increases. The second law of thermodynamics asserts that the average dissipated work is always positive for irreversible transformations, and equal to zero only when the system evolves under reversible conditions, $\langle W\rangle \geq \Delta G \Leftrightarrow \langle W_{dis}\rangle \geq 0$.

It is crucial to bear in mind that thermodynamics apply for averages over an infinite number of trajectories generated under identical conditions. They are not applicable to single trajectories.

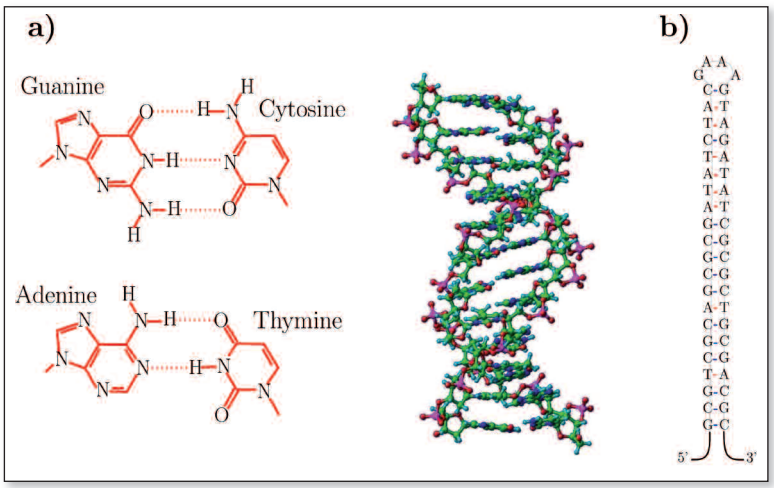
In 1997 C. Jarzynski proved a remarkable result about non-equilibrium physics [11]. Think of a system initially in thermal equilibrium with a bath at temperature T. Then a time-dependent perturbation is applied to the system and it evolves to a final state. If we assume that the microscopic dynamics of the system is Markovian then one can prove Jarzynski equality (JE):

$$\left\langle \exp\left(-\frac{W}{k_B T}\right)\right\rangle = \exp\left(-\frac{\Delta G}{k_B T}\right), \qquad (1)$$

where k_B is the Boltzmann constant. The average is taken over an infinite number of independent trajectories undergoing the same perturbation protocol. Using the JE one can recover the value of the reversible work, or the free energy difference, from measurements of the irreversible work. Moreover, it does not matter how far from equilibrium the system is driven during the experiment. Remarkably, the second law of thermodynamics can be inferred from the JE.

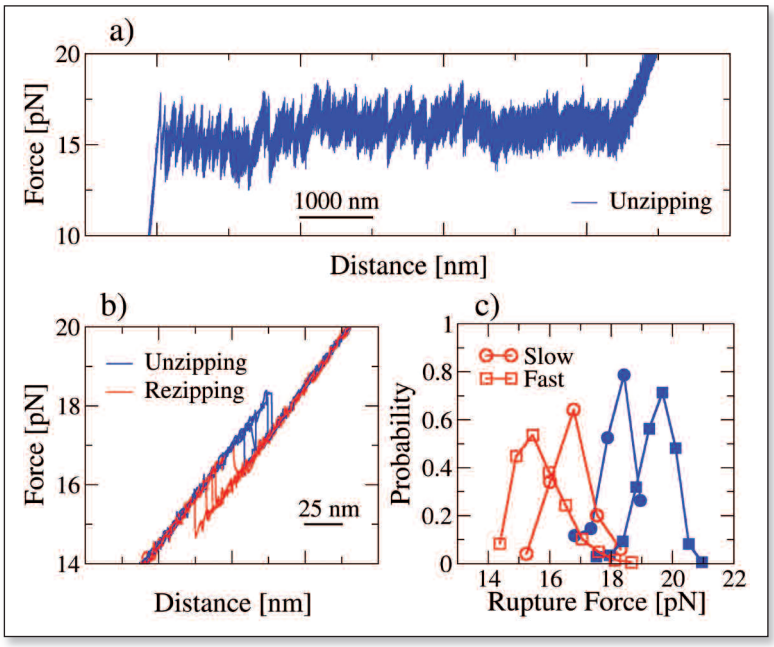
The JE implies the presence of trajectories where the dissipated work is negative, meaning that heat from the environment is absorbed by the system and converted into useful mechanical work. Despite appearances, it must be stressed that there is no violation of the second law whatsoever, because thermodynamics does not focus on single trajectories but on the average over an infinite number of them. The recovery of the reversible work from measurements of the irreversible work entails the realization of an infinite number of experiments. However, experimentalists only perform a limited number of measurements. The average of the exponential of the work becomes a finite sum of random exponentials, a strongly biased quantity displaying slow convergence to its limit. When applying the JE the most rare trajectories with smaller work values are unfairly weighed and the experimental free energy obtained is biased toward values larger than the true free energy.

Figure 4 shows results obtained with the DNA hairpin sketched in figure 2b. The pulling speed in experiments was set to 180 nm/s. The predicted free energy of formation of this hairpin at 25°C and 1M NaCl, obtained from calorimetric melting experiments, is 60.5 k_BT (35.85 kcal/mol). The free energy recovered by measuring the work (fig. 4a) and using the JE equals the free energy difference of the total system



▲ **FIG. 2: a)** DNA consists of two complementary backbones made of phosphate groups and sugars. DNA bases, guanine (G), cytosine (C), adenine (A) and thymine (T), are attached to each sugar, and its sequence encodes genetic information. The two strands form a double helix and are held together by the hydrogen bonds established between the different bases (A interacts with T and G with C). **b)** A DNA hairpin consists of a DNA double ended by a loop. The formation of the loop costs bending and twisting energy and involves a decrease in entropy. Yet, the large stability of the stem makes the whole structure thermodynamically stable. In the example, a DNA hairpin of 21 base pairs is sketched.

▼ **FIG. 3:** Examples of FDC obtained with optical tweezers. **a)** Unzipping experiment carried out at 25 nm/s (almost reversibly). The hairpin stem is 6838 base pairs long. **b)** Unzipping and zipping trajectories obtained for the hairpin shown in fig. 1b pulled at 180 nm/s. **c)** Histograms for the rupture forces obtained at different unzipping/zipping speeds: 60 (slow) and 180 (fast) nm/s.

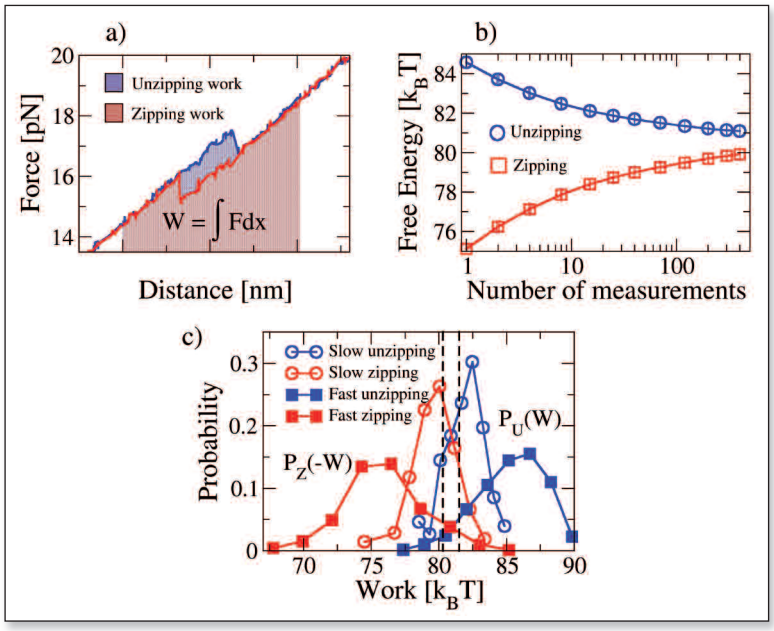


(hairpin, handles and bead) between the initial and final states. After subtracting the contributions (estimated around 20 k_BT) coming from the reversible work performed by the trap to stretch the handles, pull on the bead and stretch the elastic ssDNA released when the hairpin unfolds, we get the free energy of formation of the hairpin at zero force, 61.4±1.0 k_BT and 60.4±1.0 k_BT for the unzipping and zipping trajectories, respectively. Both cases agree well with free energies obtained from melting experiments.

Figure 4b shows the convergence of the JE with the number of measurements for both the unzipping and zipping experiments. In 1999, G. E. Crooks derived a more general relation containing the JE as a particular case and improving the mentioned slow convergence. The key point of the Crooks Fluctuation Relation (CFR) is to consider a given perturbation and its time reversed (unzipping and zipping respectively, in our case). The main result is that the free energy difference corresponds to the work value equally probably in both processes. It can be seen in figure 4c that the crossing point between the two histograms remains the same for different pulling speeds and the numbers agree with the JE.

Various FT have been demonstrated during the past two decades and experimentally tested in different systems like electrical oscillators or hydrodynamic systems [14, 15]. They have been also extended to quantum systems, which are subject to the uncertainty principle and face the intriguing difficulty of measuring work along individual experiments (where the notion of trajectory is not defined) without perturbing them. Future developments consider using FT to recover free energies in more complex situations (*e.g.*, binding free energies of proteins and other molecules or free energies of non-native states).

FT are applicable to small systems where energy fluctuations with respect to the average behaviour (of thermal or quantum origin) are big enough to be measured. The most remarkable examples of such a class of systems are found inside living organisms. Surrounded by water (and many other molecules), cells contain plenty of molecular machines and biomolecules operating out of equilibrium in a highly noisy and crowded environment. FT might provide a theoretical framework to understand how the complexity of life has emerged in such a noisy and irreversible world governed by fundamental laws that are time reversible. ■



▲ FIG. 4: a) The total work is shown as the crossed area below the FDC. b) Convergence of the free energy using the JE as a function of the number of measurements, obtained with the unzipping (blue) and zipping (red) trajectories. c) Work histograms for hairpin in fig. 2b, obtained at two different pulling speeds (60 and 180 nm/s). The crossing point remains approximately constant while dissipation increases with the speed.

About the authors

Anna Alemany graduated in physics in 2007. She is currently doing her PhD at the University of Barcelona under the supervision of Prof. F. Ritort. She is mostly interested in statistical physics with special emphasis on fluctuation theorems applied to single molecule experiments. She is currently doing unzipping experiments on DNA and RNA hairpins using optical tweezers to investigate questions related to the thermodynamics and kinetics of force-induced molecular folding and unfolding.

Felix Ritort is Professor in condensed matter physics at the University of Barcelona (Spain). His PhD received in 1991, was on spin glasses. He has made several contributions to the field of statistical physics of disordered systems, nonequilibrium systems and more recently to biophysics. Currently he runs a single molecule lab in Barcelona where he investigates questions related to the nonequilibrium physics of small systems.

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PHYSICS IN DAILY LIFE:

FUNNY MICROWAVES

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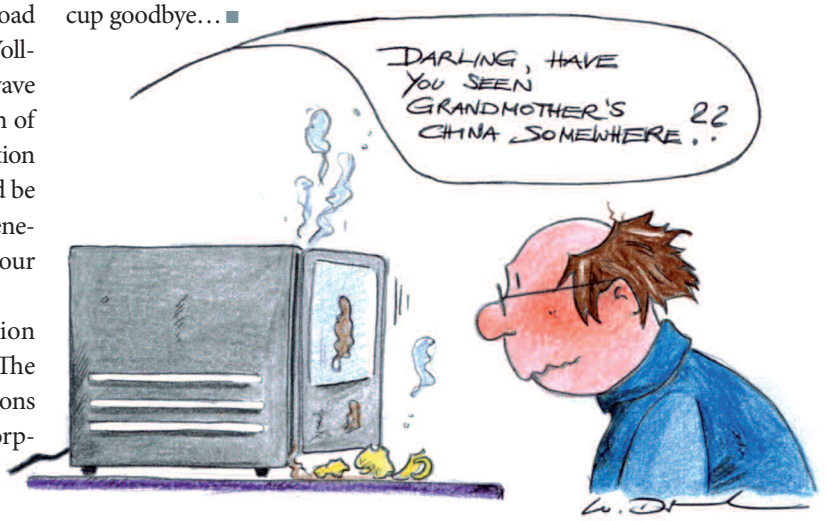
The introduction of the microwave oven (or just 'microwave', the commonly used *pars pro toto*) has made our daily lives much easier. As physicists we may be a bit misled by the name and think of micrometers. But the standard oven operates at a frequency of 2,45 GHz, which corresponds to a wavelength of some 12 cm. That's not precisely in the middle of the microwave region. This wavelength does explain though that, given the typical oven size, standing wave patterns can cause large intensity differences over our food. We also realize that we need a convenient absorber in our food: water. But the absorption mechanism is not trivial. It is *not* some intramolecular vibration or rotation mode that we are using. Typical rovibrational bands involve much higher energies, such that they are even responsible for the strong absorption in the red part of the visible spectrum in water. Instead, we use the large dipole moment of the water molecule to make it 'wiggle' amidst its neighbours. To be more precise: we absorb radiation by dielectric loss due to dipole relaxation. The microwave region is perfect for that. At much lower radiation frequencies the dipoles would follow the field changes and there would be no absorption. At very high frequency the dipoles have no time to change their orientation, and again nothing much happens. In between, where the dipoles lag behind the field, we expect a broad absorption curve. As already elucidated by Michael Vollmer in Physics Education back in 2004, the microwave frequency employed is not even near the maximum of the absorption curve. If that were the case, the absorption would be so large that only a thin layer of food would be heated. Instead, the frequency used is such that the penetration depth is in the order of a few cm, allowing our food to be heated more evenly.

An interesting consequence of the dipole relaxation mechanism is that ice has very little absorption. The molecules are simply too fixed in their lattice positions to follow the oscillating field. This reduces the absorption by three to four orders of magnitude.

So much for liquid or solid water in our oven: what about metals? Of course, reflection of the microwaves is almost perfect, due to the free electrons which essentially re-radiate the microwaves. Their penetration depth into the metal is in the order of 1 μm only. So our kitchen should be perfectly safe ground as long as we keep the oven closed. And it should be no problem to leave a spoon in our cup of tea. A fork may be risky, though. Its sharp extremities will concentrate the electric field lines just like a lightning conductor does, and may lead to breakdown, with an interesting but possibly harmful light show as a result.

The most spectacular show may be caused by our precious decorated china, especially if the decoration is a thin gold layer. The reason is not trivial. We must remember the extremely small penetration depth of the microwaves in metals. Inside that thin layer a lot of heat will be dissipated. For a solid metal piece like a spoon, this poses no problem. Its thermal conductivity and heat capacity are large, so it can easily absorb the heat and transfer it to the fluid in the cup. Alas, our china cups are poor thermal conductors, and the heat has nowhere to go but to the tiny thermal mass of the metal. So if we absent-mindedly put our beautifully decorated cup of tea in the microwave, we may have to kiss that cup goodbye… ■



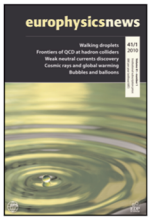
EUROMAGNET CALL FOR PROPOSALS FOR MAGNET TIME

The next deadline for applications for magnet time at
the **LABORATOIRE NATIONAL DES CHAMPS MAGNETIQUES INTENSES**
(ex GHMLF & LNCMP / http://lncmi.cnrs.fr)
the **HIGH FIELD MAGNET LABORATORY** (www.hfml.science.ru.nl)
and the **HOCHFELD LABOR DRESDEN** (www.fzd.de/hld)
is May 15th, 2010.

Applications can be done trough an on-line application form on the web site: http://www.euromagnet.org from April 15th, 2010.

Scientists of EU countries and Associates States* are entitled to apply under FP7 for financial support according to the rules defined by the EC.
*listed on ftp://ftp.cordis.europa.eu/pub/fp7/docs/third_country_agreements_en.pdf

For further information concerning feasibility and planning, please contact the facility of your choice.



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IWF Space Research Institute

The Space Research Institute of the Austrian Academy of Sciences is involved in many international space missions and cooperates with the European Space Agency (ESA) and with other national space agencies (NASA, CNES, JAXA).

ÖAW Austrian Academy of Sciences

Our present satellite geodesy activities concentrate on the application of laser, microwave, and gradiometer observation techniques for the determination of satellite orbits and the Earth's gravity field. We are planning to extend these activities to other solar system objects.

We are looking to fill a position of a

Group Leader

for the investigation of the terrestrial and planetary gravity fields based on satellite missions.

Scientific Qualification:

- University degree, preferably in Geodesy, Geophysics, Planetology
- Scientific expertise in the field of space geodesy in general with a particular focus on gravity field determination
- The successful applicant is expected to build up and lead a new team, which in the end will cover all aspects of terrestrial and planetary gravity field research. These include participation in space missions, data analysis, modeling, and (geo-)physical interpretation.

Please address your application including a curriculum vitae and a research plan until April 30, 2010 to

Space Research Institute
Austrian Academy of Sciences
Attn: Ms. Claudia Grill
Schmiedlstraße 6, A-8042 Graz
claudia.grill@oeaw.ac.at | www.iwf.oeaw.ac.at

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

PAUL SCHERRER INSTITUT PSI

Assistant Professor (Tenure Track) of Physics of Ultrafast Phenomena

The Department of Physics at ETH Zurich (www.phys.ethz.ch) invites applications from candidates who pursue a strong research program in the physics of ultrafast phenomena. Emphasis will be on the use of short coherent X-ray pulses for research on the ultrafast dynamics of condensed matter systems and for imaging matter on the nanometer scale. The Department of Physics offers a stimulating environment in experimental, theoretical, and computational physics. The nearby Paul Scherrer Institute (www.psi.ch) provides access to first class experimental facilities (Swiss Light Source, including Femtosecond X-ray pulses at the FEMTO beamline, Swiss Spallation Neutron Source, and Swiss Muon Source). An X-ray Free Electron Laser (SwissFEL) is presently in the planning stage.

The successful candidate will play a leading role in the design, realization, and use of this facility. Teaching at ETH Zurich involves contributions to the physics curriculum at the Bachelor (German and English) and Master's (English) levels.

Assistant professorships have been established to promote the careers of younger scientists. A generous funding package is available for this post. The initial appointment is for four years with the possibility of renewal for an additional two-year period and promotion to a permanent position.

Please submit your application together with a curriculum vitae, a list of publications, and a brief statement of present and future research interests **to the President of ETH Zurich, Prof. Dr. Ralph Eichler, ETH Zurich, Raemistrasse 101, 8092 Zurich, Switzerland (or via e-mail to faculty-recruiting@sl.ethz.ch), no later than May 31, 2010.** With a view towards increasing the number of female professors, ETH Zurich specifically encourages qualified female candidates to apply.

The Nanosciences Foundation is launching a call for

Chairs of Excellence

The Nanosciences Foundation fosters basic research on Nanosciences in Grenoble (France) by supporting a network of **32 laboratories** gathering about **1000 researchers** and funding collaborative and multidisciplinary projects on an international level.

The Foundation is launching a program "Chairs of Excellence" to attract talented researchers in Grenoble willing to develop in one of its laboratories an innovative and ambitious project dedicated to emerging fields of nanosciences.

The award package includes : an internationally competitive salary, social security, travel expenses and financial support for hiring a PhD student and a post-doc, plus additional funds for operating costs to reinforce the successful candidate's research activities.

The program is open to both junior and senior scientists, available for full time or part time position, from 9 months to 3 years. The hosting period may start from January 2011.

To know all the details about this unique opportunity, visit our website on:

http://www.fondation-nanosciences.fr/RTRA/en/200/Chairs_Program_2010.html

nano SCIENCES FONDATION

The Foundation for Fundamental Research on Matter (FOM) promotes, coordinates and finances fundamental and applied physics research in the Netherlands. It is an autonomous foundation responsible to the physics division of the national research council NWO. FOM employs about 950 people, primarily scientists (including PhD students) and technicians, who work at FOM research institutes and university laboratories. In addition to the funding of NWO, FOM acquires financial means from industry and the European Union. In the frame of its valorisation policy FOM actively pursues research programmes through partnership with industry and the establishment of FOM research groups in industrial research environments.

FOM

Project Leader Extreme UV-induced Surface Processes

The FOM-Institute for Plasma Physics Rijnhuizen is seeking candidates for a tenure-track staff position as leader of a scientific research group on ion- & photon induced surface chemistry and physics. The group is to be established at the research laboratory of the leading semiconductor equipment manufacturer ASML, Veldhoven, centred around its unique Extreme UV radiation and analysis facilities. The research programme of the group will be part of a recently granted, flagship Industrial Partnership Programme to be jointly carried out by FOM-Rijnhuizen, ASML, and it's optics partner Carl Zeiss SMT AG.

Research field. The interaction of high-intensity ion and photon beams with solid-state surfaces is a fundamental and fascinating process, which is at the very focus of advanced photolithography. New classes of EUV-optical, multilayered structures are investigated for usage at extremely high photon fluxes, necessitating fundamental studies on ion- and photon induced surface reactions and photo- and plasma chemistry in general. The scientific programmes at Rijnhuizen, Zeiss, and ASML include world-leading research activities in each of these areas, using a unique suite of high flux photon sources and ion beam generators, equipment to study surface photochemistry from the infrared to the extreme UV, layer growth set-ups, and state-of-the-art surface analysis facilities.

Qualifications. Applicants should have a PhD degree in Physics or Chemistry and a proven post-doctoral record of excellent and original experimental work on either surface photochemistry, plasma physics, plasma/ion surface interactions, thin film physics, or material science. The candidate is expected to have an international stature in one of these areas, borne out by a well-cited publication record, invited talks at international conferences, etc. Proof of leadership skills, ability to produce top-quality scientific research results, experience in project acquisition, and successful collaborations with industry are prerequisites.

Employment conditions. FOM offers a stimulating work environment in an area of applied, forefront research bridging academic and industrial research environments. The successful candidate will receive a competitive start-up package, with many opportunities to attract external funding and establish an active and well-visible research group. The position is intended as full-time for the duration of five years, with possibility for tenure afterwards if performance criteria have been met. The salary will be commensurate with experience and qualifications, with a maximum of € 69.770,- gross per year, including holiday allowance and end of year bonus. Retirement benefits are arranged via the 'Stichting Pensioenfonds ABP', while employment conditions are laid down in the 'CAO onderzoekinstellingen'.

Information on employment conditions and working at FOM can be found at www.fom.nl under 'personnel'. Ongoing research is listed at www.rijnh.nl/research/nsi/; the Rijnhuizen Strategic Plan 2008-2013 will be sent upon request. For more information about this position you may contact Prof.dr. Fred Bijkerk or Prof.dr. Aart Kleyn (both via +31 (0)30-6096749, or at f.bijkerk@rijnhuizen.nl).

Applications. Applications, including resume, publication list, names of three referees, and a detailed research statement, can be sent before before April 16th, 2010 to drs. Karijn Heling, FOM-Institute for Plasma Physics Rijnhuizen, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands, or by e-mail to: vacancies@rijnhuizen.nl. Please note 'vac. nr. 10-002/nSI' in your application letter.

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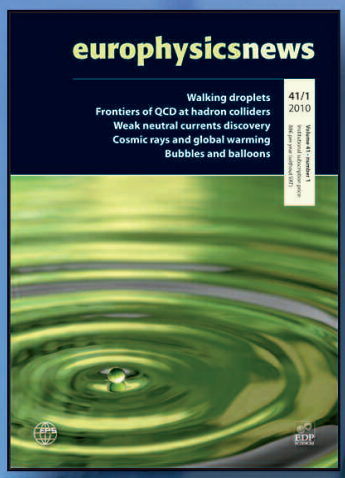

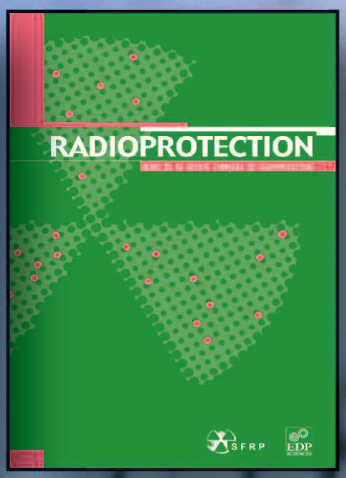

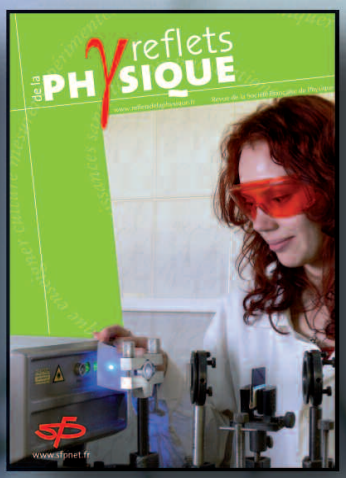

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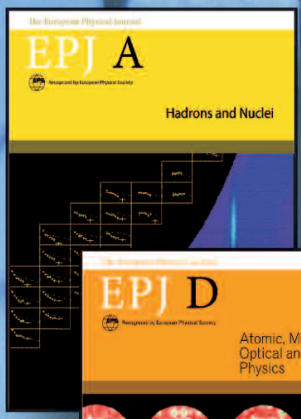

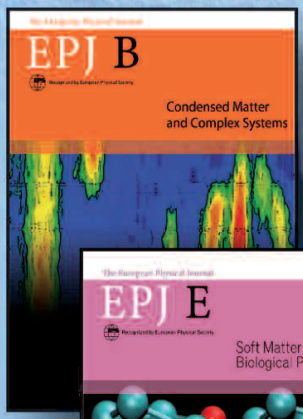

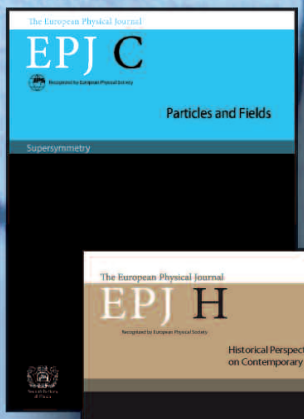

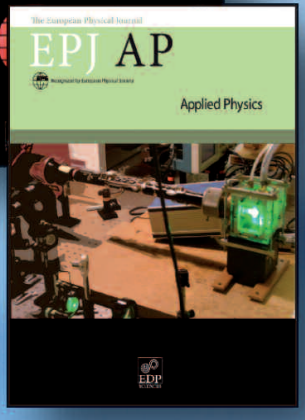

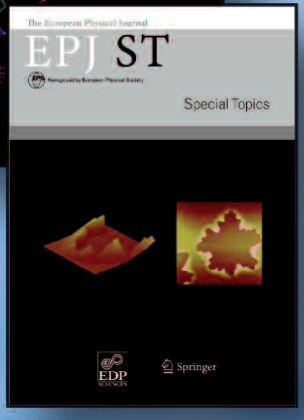

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