

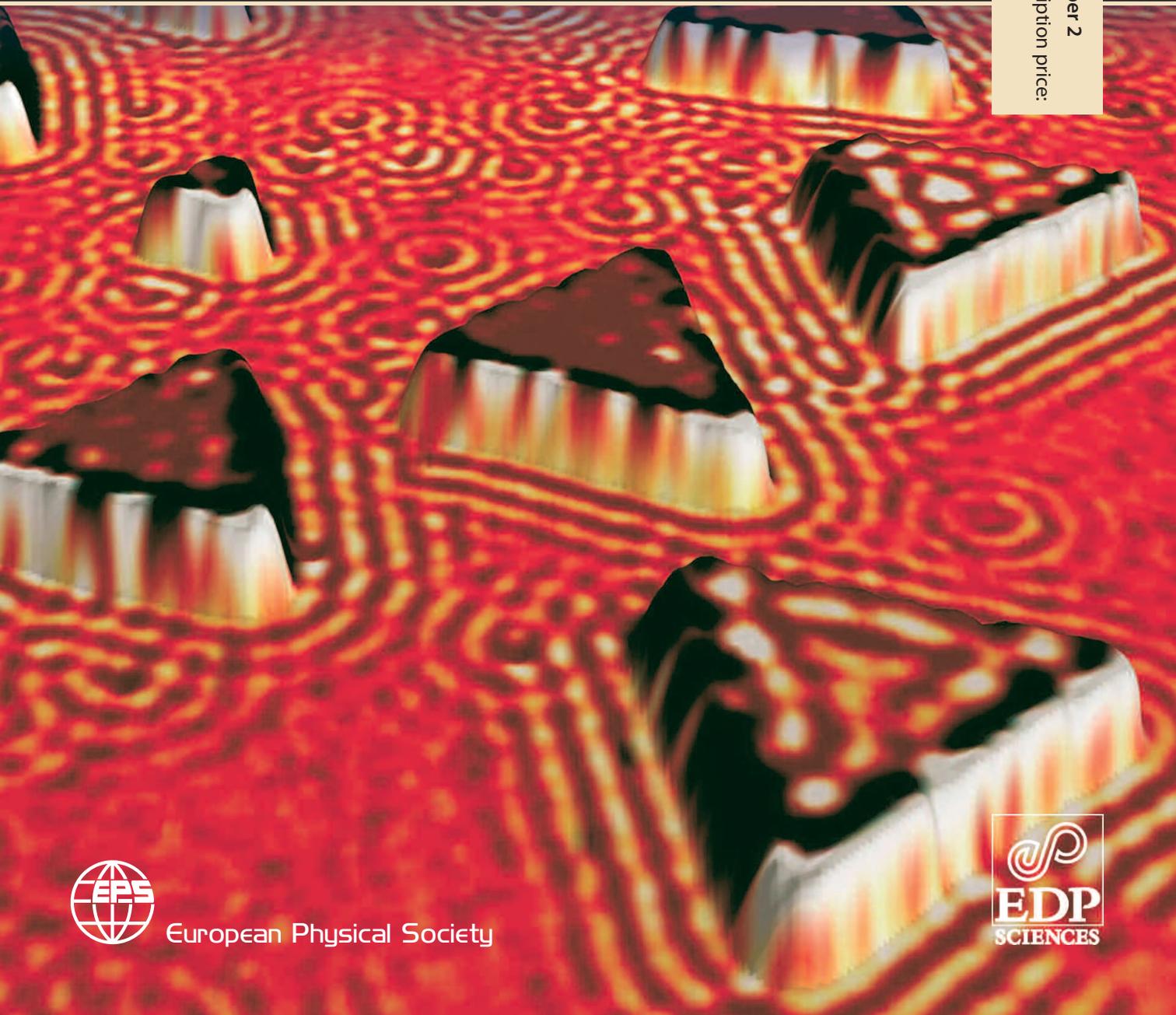
# europhysicsnews

Mapping spin structures on the atomic scale  
Carpet of magnetic colours  
Directory  
Revisiting the thorium-uranium nuclear fuel cycle  
Towards nanospintronics

38/2

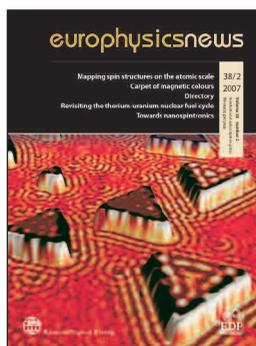
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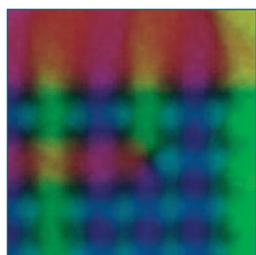
2007 • Volume 38 • number 2

**Cover picture:** Nanoscale Co islands of two atomic layers height grown on a Cu(111) substrate: STS image, perspective-view (see article p.16)



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Hearing the curtains

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# Cohesion and EPS [EDITORIAL]

EPS is a society based on members in 40 European countries. Close to 100,000 physicists are active, all in their own right, and they have, presumably, all joined with the aim of improving working conditions for physics research and education in Europe. This is a daring task comparable to the Sisyphus myth. Work needs to be exercised continuously and with results often being status-quo at best.

This is and has always been the starting point for EPS in its work to further the status of and the possibilities for physics in Europe. Being a society, EPS depends crucially on the voluntary work many physicists generously donate to EPS. I talk about editors and boards of directors of the EPS scientific journals, of individuals organizing EPS sponsored conferences, program chairs, division boards and members of the many EPS task forces.

I also include the many physicists who work for the advancement of physics in all our member countries. Not based on exact science a rough count could be between 2000 – 3000 physicist “working for” EPS in various capacities. This is a surprisingly large number, pointing to the backbone of our society, which will celebrate its 40<sup>th</sup> anniversary next year. The first 40 years have been challenging, but with the last 10 years clearly pointing forward towards the next 40 years.

EPS enjoys the benefits of its own facilities in Mulhouse, a competent staff and a stronger and stronger standing within the policy frames in Europe. The recent first prize for *organized civil society* awarded to EPS by the European Economic and Social Committee is one such manifestation as is also the formation of the new Forum Physics and Society (Editorial, EPN 37/6, 2006). Indeed, EPS is well prepared for continued growth in the coming years.

During the last two years I have had the privilege to head EPS and in this capacity visit many countries in Europe. In all these visits I found spirits very high and the local communities prepared for the uphill struggle to attract resources for research infrastructure or better facilities for advanced education. The challenge faced by the former countries in Eastern Europe is of a particular difficult nature. The possibility of using EU infrastructural funds to assist in the building of a scientific infrastructure has merit and should allow for faster and more decisive progress.

Why is this important? For several reasons, the first of course being the strong role traditionally played by physics in the interface between new disruptive technologies and classical engineering-based technology. In other words, physics is needed as a key player in the Pasteur Quadrant analysis of wealth creation.

There is a second and equally important reason why physics should be strong in all the EPS member countries, namely the educational necessity broadly defined within the realm of science and technology. The EU coordinated Bologna process is a challenge to physics and to physicists in Europe, more so than perhaps is realized today.

The third reason is a more subtle one. From my perspective it is also the most important and often an undervalued reason why an investment in physics (and science) is worthwhile for society. It has to do with the strength of society’s cohesion. Physicists represent a strong and independent culture not easily manipulated by society. Thus physicists are important in defining a mirror in which society never will be able to “see what it wants” but rather see “what it should see”. It is clear when looking around the world, that strong science systems are a stabilizing factor in a societal context. More so, as we have witnessed, our fellow physicists have played crucial roles in recent adjustments of government structures out of tune with our ideas of society.

I have worked, on and off, with EPS since the early nineties, more than 15 years. My term as President is coming to an end. However, this is not a farewell to EPS. There is a strong tradition, that EPS senior officials can and will continue working for our society. I am happy to continue working with educational issues, hopefully cracking the scientific publication dilemmas and not losing hope that gender mainstreaming may be accomplished.

Ove Poulsen, EPS President.

# Highlights of physics [PHYSICS FESTIVAL]

EVERYTHING started in 2000 – the German “Year of Physics”. The Federal Ministry of Education and Research as well as the DPG (German Physical Society) organized a whole year around physics. Everywhere in the country, talks, exhibitions and other events about and around physics took place – and people liked it! It was the first time that science was so close to all citizens – children and their parents, school classes, older people and everyone interested in physics joined the numerous events on display. After this great success the two institutions wanted to keep the fire of interest burning and so in 2001 they started an annual festival of physics called “Highlights of Physics”.

Since 2001 this event, lasting one week, has taken place in different German cities: Munich, Duisburg, Dresden, Stuttgart, and specifically in Berlin during the World Year of Physics 2005. On 6-10 November 2006 it was organized in Bremen. The aim of this event is to bring physics closer to people, to show them the fascination of science, to open their eyes to the wonders of nature and to the fact that man is able to understand (or at least to describe) it. And what should we say – it definitely works! Visitors have the opportunity to talk with scientists, to experience the spirit of research and to obtain some understanding of the things they are doing. “Scientists are starting to get out of their ivory towers.” said Prof. Eberhard Umbach, president of the DPG.

The “Highlights of Physics” 2006 in Bremen began with a phenomenal 3-hours show, moderated by a well-known German physicist and show-master in front of an audience of about 1700 people. Many experiments on sounds and tones, even using an original Stradivarius violin, were presented in addition to comedy

acts, magic shows, and finally a discussion about the role of science in our society.

With this year’s subject “World of waves – from violins to monster waves” about 30 groups of scientists presented their results in a permanent fair in the Bremen Congress Centre. More than 6000 visitors used the opportunity to become informed about interference phenomena, gravitation waves, the origin of Tsunamis and a lot more.

During the whole week, lectures on waves and their properties were presented, supplemented by special talks for school classes, physical entertainment shows and evening presentations. In particular shows like “Magic Andy” or the “Physikanten” made people wonder about physical phenomena such as the functionality of a singing bowl, the tunes originated by a laser guitar or whatever can be done with a microwave oven besides heating meals.

Another action of “Highlights of Physics” is a scientific competition for pupils. With this year’s theme on “exciting physics” the children were asked to build ‘chucking’ machines for tennis balls, non-motorized but moving robots, or cranes made of paper. Their creations were then compared and evaluated by their ability to perform specified tasks. As in every year, hundreds of pupils took part in this mind-widening contest, attracted by high-class awards. The great variety of ideas, the good knowledge the young people had gained and the familiarity with their problems was highly regarded by university teachers of the jury. If physics can bring a lot of fun, studying physics nevertheless means working hard in a very challenging field. This is one of the messages that “Highlights of Physics” wants also to convey through this competition.

Even the youngest (age < 6) were asked to attend the “Highlights”. Thus many children with their kindergarten groups responded to this invitation and spent some time in the “kindergarten laboratory”. They played with water drops



▲ Excited children watching experiments in the “kindergarten laboratory”

running through a two phase liquid system and watched with fascination the drop changing its appearance. “It is important to maintain this interest of the very young and the ability to ask simple questions”- said Jörn Birkhahn, the initiator of this event (more information: [www.kindergartenlabor.de](http://www.kindergartenlabor.de))

In the evening talks, exciting topics made people leave their TVs at home. Prof. Mojiib Latif (IFM Geomar, Kiel) pinpointed the current facts of global warming and explained the potential scenarios that will lead to consequent temperature rises by 2100. Ulf Merbold, a German astronaut, reported about his space-flights, the fascination and privilege of observing earth from above, whereas Prof. Metin Tolan (University of Dortmund) explained the physics behind the James Bond films – expanding even on why 007 drinks his vodka martini shaken and not stirred.

*It was another great success in the history of the “Highlights of Physics”* was the summary of Dr. Axel Carl, responsible for the event. If everything goes according to plan, the next event should take place in summer 2007 in Frankfurt. ([www.highlights-physik.de](http://www.highlights-physik.de)). ■

René Pfitzner and Alexander-C. Heinrich

## About the authors

The two authors are members of the jDPG, the “young German physical society” a work group within the DPG. It has existed since December 2005 and has about 43 active members. The jDPG was founded to provide meetings, seminars, field trips etc. for the numerous collegiate members of the DPG as well as representing them democratically within the DPG.

◀ Federal Minister of Education and Research, Dr. Annette Schavan; DPG-president, Prof. Dr. Eberhard Umbach; Education Senator of Bremen, Willi Lemke; and IUB-president, Prof. Dr. Joachim Treusch talking about the role of science in our society



# Science historian R.H. Rashed awarded [PRIZES]



▲ Roshdi Hifni Rashed

THE King Faisal Foundation [1] in Riyadh, Saudi Arabia has announced that science historian, Roshdi Hifni Rashed is the recipient of the 2007 *King Faisal International Prize for Islamic Studies* (Topic: *Muslims' Contribution to Pure or Applied Sciences*), with a cash prize of

200,000 dollars. He was declared the winner in this category in recognition of his insightful studies, authentication, commentaries and translations of contributions of Muslims to pure science, in particular their achievements in the fields of *mathematics* and *optics*. Roshdi Rashed has translated several little known manuscripts, bringing recognition to some of the medieval Arab contributors of science, whose manuscripts were otherwise just

lying unnoticed in libraries & museums. Roshdi Rashed is particularly recognized for his illustrious, six-volume *Encyclopedia of the History of Arabic Science* and his four-volume book on *Analytical mathematics during the ninth-eleventh centuries*. Rashed was born in Egypt in 1936 and received his doctorate for a history of the philosophy of mathematics from the University of Paris (2). He is an Emeritus Research Director (Distinguished Class) of the French National Centre for Scientific Research (CNRS)

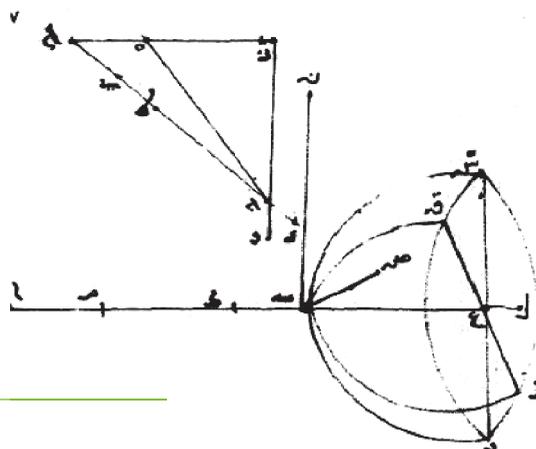
and Honorary Professor, Tokyo University, Japan. ■

Sameen Ahmed Khan,  
Salalah College of Technology, Sultanate of Oman

## References

- [1] King Faisal Foundation: [www.kff.com/english/kfip/2007/islamicstudies.html](http://www.kff.com/english/kfip/2007/islamicstudies.html)  
[2] Further details about Roshdi Rashed: <http://chspam.vjf.cnrs.fr/Personnel/Rashed.htm>

► In 1990 Rashed made the historical discovery that the geometric description of refraction, hitherto attributed to Snell, Descartes, and/or Fermat in its sine-law form, was already known and written upon by Abu Sa'd al-'Ala' Ibn Sahl (940–1000) working in the Abbasid court in Baghdad. The following diagrams for Refraction and the Plano-Convex Lens are reproduced from Ibn Sahl's book, 'On the Burning Instruments', written in 984 (courtesy Milli Library, Tehran).



# Scholar Rescue Fund fellowships [EDUCATION]

THE Institute of International Education's Scholar Rescue Fund provides fellowships for scholars whose lives and work are threatened in their home countries. These fellowships permit scholars to find temporary refuge at universities and colleges anywhere in the world, enabling them to pursue their academic work and to continue to share their knowledge with students, colleagues, and the community at large. When conditions improve, these scholars will return home to help rebuild universities and societies ravaged by fear, conflict and repression.

## How the Scholar Rescue Fund works:

> Academics, researchers and independent scholars from any country, field or discipline may qualify. Preference is given to scholars with a Ph.D. or other higher degree in their field; who have extensive teaching or research experience at a university, college or other institution

of higher learning; who demonstrate superior academic accomplishment or promise; and whose selection is likely to benefit the academic community in the home and/or host country or region.

Applications from female scholars and under-represented groups are strongly encouraged.

> Fellowship recipients are expected to resume their teaching, lecturing, research, writing and publishing at an academic institution outside the region of threat.

> Fellowships are awarded for visiting academic positions ranging from 3 months to one calendar year. The maximum award is US \$20,000.

> Fellowships are disbursed through host academic institutions for direct support of scholar-grantees. In most cases, host campuses are asked to match the SRF

fellowship award through partial salary/stipend support, research materials, medical insurance, and other in-kind assistance.

> Applications are accepted at any time. Emergency applications receive urgent consideration. Non-emergency applications will be considered according to the following schedule:

**Spring 2007:** Application received by April 1; decision by June 1.

**Fall 2007:** Applications received by September 1; decision by November 1.

## For more information about the Fund, contact:

IIE, Scholar Rescue Fund Fellowships  
809 U.N. Plaza, Second Floor,  
New York 10017

Tel: (USA) 1-212-984-5472,

Fax: (USA) 1-212-984-5353

E-mail: [SRF@iie.org](mailto:SRF@iie.org),

Web: [www.iie.org/SRF](http://www.iie.org/SRF) ■

# ESCAMPIG 18 [CONFERENCE REPORT]

Mario Cacciatore<sup>1</sup> and Santolo De Benedictis<sup>2</sup>  
<sup>1</sup>(Chairman LOC) / <sup>2</sup>(Co-chairman)

THE 18<sup>th</sup> European Sectional Conference on Atomic and Molecular Physics in Ionised Gases (ESCAMPIG 18) was held at the Grand Hotel Tiziano in Lecce in the south of Italy, from July 12 till July 16, 2006. The conference, hosted in Italy for the second time after the meeting held in Bari in 1984, was organized by the Institute of Inorganic Methodologies and Plasma (IMIP) of the Italian National Research Council and by the Chemistry Department of Bari University. The aim of the Conference was to bring together scientists, researchers and students from European Laboratories who are working in the broad area of the physics and chemistry of ionized gases and plasma. It is also a long-standing tradition of ESCAMPIG to have some outstanding invited speakers and contributions from non-European countries.

Following the unique format of all ESCAMPIG conferences, the Conference represented the overall state of the art in the following fields: atomic and molecular processes in plasmas, particle energy distribution functions, discharge physics, plasma diagnostics, plasma processes assisted by laser and particle beams, physical basis of plasma chemistry and plasma surface interactions.

Special sessions were dedicated to two workshops on: a) plasmas and nanomaterials and b) fundamental processes in laboratory and natural plasmas.

More than 200 participants from 23 European countries (France, Germany, Romania, Czech Rep, Russia, Portugal, Spain, The Netherlands, United Kingdom, Serbia Austria, Estonia, Ireland, Latvia, Norway, Poland, Turkey, Belgium, Croatia, Hungary, Swiss) and 4 non-European countries (Japan USA, Canada, Mexico) were welcomed in Lecce. A significant number of PhD students and young researchers from the European Union and East-European countries received support from the EPS and from the Local Organizing Committee. Invited speakers were also supported, thanks to sponsorships from Italian scientific institutions and European companies.

The scientific programme consisted of 16 invited lectures (8 invited general lectures of 45 minutes, 8 topical lectures of 30 minutes), and 200 poster presentations. There were also 7 'hot topic' presentations of 15 minutes selected by the scientific committee, chaired by Prof. B. Graham, from the abstracts submitted. The workshop topics were focused on 12 selected contributions. Most of the invited lectures and 'hot

topic' presentations have been peer reviewed and published in *Plasma Sources Sciences and Technology*.

Various invited lectures and poster contributions provided a wealth of information on the elementary steps in complex physic-chemical processes, thus bridging the fundamental and applied aspects of reactive gases and plasmas. The dual aspect of research carried out by the scientific community which comes together at ESCAMPIG, namely the development and application of methods for characterising and controlling atomic and molecular processes and the use of plasma systems in various technological and applied science fields, was evident in the various contributions and discussions. And indeed, this was one of the targets of the present ESCAMPIG.

A significant participation from Japan confirmed the large interest in the exchange of ideas and networking between the Japanese and the European communities working in the research area of low-temperature plasmas.

The lively atmosphere in the GH Tiziano, which allowed relaxed and informal scientific contacts and discussions, certainly contributed to the success of the Conference. ■



## EDM 2007

European Discussion Meetings on Polymer Crystallisation

under the auspices of the **European Physical Society**  
and within the framework of **COST P12**

**3 - 6 October 2007**

**Waldau / Hochschwarzwald • Germany**

website: [www.edmconference.org](http://www.edmconference.org)

# ECOSS 24 [CONFERENCE REPORT]

Jacques Jupille<sup>1</sup> and Paul Dumas<sup>2</sup>

<sup>1</sup>(chair) INSP, Université Pierre et Marie Curie, Paris • France / <sup>2</sup>(vice-chair) Synchrotron SOLEIL, Saint-Aubin • France

THE 24<sup>th</sup> European Conference on Surface Science (ECOSS 24) was held in Paris, September 4 to 8, 2006. It continued a series which started in 1978 and has a long tradition. Organised under the auspices of the European Physical Society through its Surface and Interface Section, the ECOSS series is a major worldwide event in fundamental surface physics. A present concern of Surface Science is the study of low-dimensional objects, tackled with the use of near-field microscopies. After being for long confined to ultrahigh vacuum preparations and techniques, Surface Science now deals with realistic substrates and conditions (from metals to insulators, from inorganic to biological substrates, from vacuum to liquid environments) and raises a number of scientific challenges, such as understanding adhesion, lubrication, sensors, biocompatibility, catalysis and functional thin films...

Following ECOSS 23 in Berlin, in 2005, which had attracted the unprecedented number of 900 attendees, the Conference in Paris brought together 820 scientists from 46 countries. The number of participants at these last two events shows a net increase with respect to previous ones. The burgeoning links of Surface Science with other scientific areas is a likely explanation for this increased interest. Another proof of the vitality of the domain was given by the participation of 250 PhD students in the event.

Besides the twelve topical sessions (Adhesion, friction and tribology; Adsorption and reactions at surfaces; Biomaterial Interfaces; Clusters and thin films, growth and properties; Dynamical processes at surfaces; Electronic properties; Ionocovalent surfaces and interfaces;

Liquid-solid interfaces; Manipulation at the nanoscale; Molecular self-assembly and supra-molecular structures; New experimental approaches for surface and interface; Surface alloys; Surface magnetism; Surface structure and phase transitions), the scientific programme of ECOSS included five symposia aimed at illustrating the fast-developing areas of surface science, such as: *defects on oxides, from single molecule to molecular electronics, plasma-surface interactions, ultrafast dynamics at surfaces, water surfaces and interfaces* which met expectations by attracting large audiences. The whole programme was organized in five parallel sessions and three poster presentations. Four plenary talks and 34 invited topical talks highlighted the basic, cutting-edge research in the physics and chemistry of surfaces while the quality and the diversity of the communications, both oral and posters, allowed the conference to be a lively forum for discussions and debate. Participants have presented a total of 280 oral communications and more than 600 posters.

In organizing the Paris Conference, an effort was made to improve the gender balance at the highest level of the conference, by inviting more than one woman for every five persons on the International and Programme Committees, on the Panel of Invited Speakers, as well as on the Panel of Session Chairs. In this respect, the conference was still far from parity, but a hope is that future events will show continuous progress in that direction.

The next Conference of the series, ECOSS 25, will be held in Liverpool, 2008, under the chairpersonship of Professor Steve Holloway. ■



◀ Photo "prize": Marcello D. Ackermann, from Leiden University (The Netherlands) receives the 2006 ECOSS-Prize for his communication on "A detailed look at palladium as CO oxidation catalyst: from atomic detail to reactor oscillations" from Pr. Dr. Klaus Wandelt, President of the ECOSS Committee (right) in the presence of the ECOSS 24 chair, Dr. Jacques Jupille (centre). The ECOSS-Prize is awarded after a communication based on a PhD-thesis, which must have been defended less than one year before the conference. Eight candidates, pre-selected from more than 100, were competing for the 2006 ECOSS-Prize at the conference.

## Conference Announcements

### 9<sup>th</sup> ECLC

The 9<sup>th</sup> European Conference on Liquid Crystals is scheduled for July 2-6, 2007 in Lisbon, Portugal. This conference will cover all major topics in Liquid Crystals Science and Technology, as well as related topics in Biology and Soft Materials. ■

#### > Website:

<http://events.fct.unl.pt/eclc2007/>

### PHONONS 2007

The 12<sup>th</sup> International Conference on Phonon Scattering in Condensed Matter, will be held on July 15-20, 2007 in Paris, France. This conference is held every three years and continues the series started in 1972. Both theoretical and experimental results in phonon physics and related phenomena will be covered. ■

#### > Website:

[www.isen.fr/phonons2007/](http://www.isen.fr/phonons2007/)

### VAS 12

Erice, Sicily, will host the 12<sup>th</sup> International Conference on Vibrations at Surfaces, July 20-26, 2007. The Conference will bring together experienced researchers and students working in surface vibrational spectroscopy, surface dynamics and in the development of new techniques for their understanding, in the fields of physics, chemistry, biology and engineering. ■

#### > Website:

[www.fisica.unige.it/~vas12/](http://www.fisica.unige.it/~vas12/)

### CCP 2007

The Conference on Computational Physics will take place in Brussels from 5 to 8 September 2007. ■

#### > Website:

<http://ccp2007.ulb.ac.be>

# Highlights from european journals

## Nano-scale phase transitions

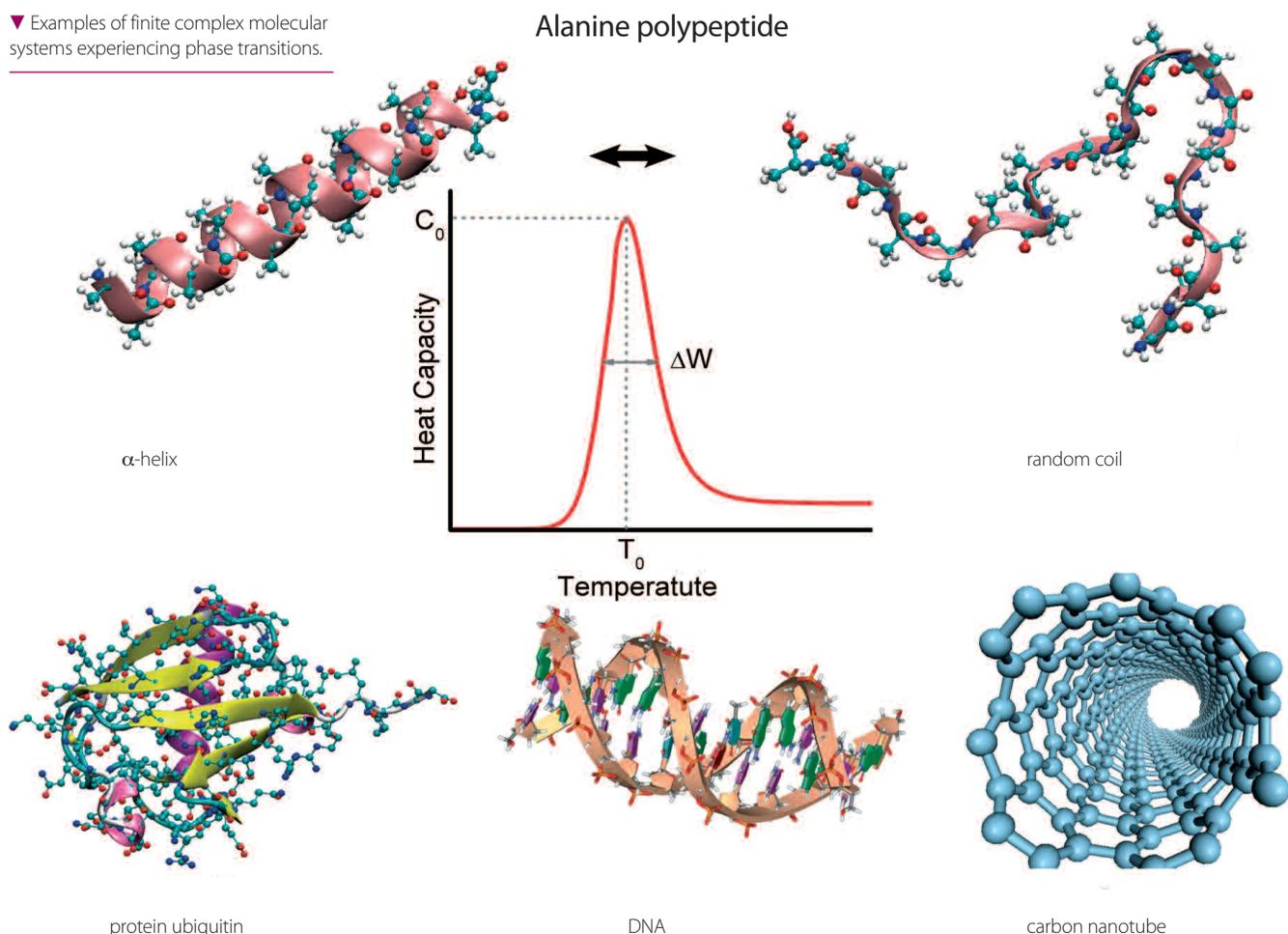
The phase transitions (PTs) in finite complex molecular systems, *i.e.* the transition from a stable 3D molecular structure to a random coil state or vice versa (also known as a folding process), has a long standing history of investigation. The PTs of this nature occur or can be expected in many different complex molecular systems and in nano objects, such as polypeptides, proteins, polymers, DNA, fullerenes, nanotubes (see Figure). They can be understood as first order PTs, which are characterized by a rapid growth of the system free energy at a certain temperature. As a result, the heat capacity of the system as a function of temperature acquires a sharp maximum at the PT temperature. We have developed a novel *ab initio* theoretical method for the PT description of the aforementioned molecular systems. In particular,

it was demonstrated that in polypeptides one can identify specific twisting degrees of freedom responsible for the folding dynamics of the amino acid chain. The essential domain of the potential energy surface of polypeptides with respect to these degrees of freedom can be calculated and thoroughly analysed on the basis of *ab initio* methods such as density functional theory or the Hartree-Fock method. This knowledge is sufficient for the construction of the partition function of a polypeptide chain and thus for the development of its complete thermodynamic description, which includes calculation of all essential thermodynamic variables and characteristics, *e.g.* heat capacity, PT temperature, free energy etc. The method has been proved to be applicable for the description of the PT in polyalanine of different length by

the comparison of the theory predictions with the results of several independent experiments and with the results of molecular dynamics simulations. Comparison of the results of this method with the results of molecular dynamics simulations allows one to establish the accuracy of the new approach for molecular systems of relatively small size and then to extend the description to larger molecular objects, which is especially essential and interesting in those cases when molecular dynamics simulations are hardly possible because of computer power limitations. ■

A.V. Yakubovich, I.A. Solov'yov, A.V. Solov'yov and W. Greiner,  
 "Ab initio description of phase transitions in finite bio-nano-systems", *Eur. Phys. J. D* 40, 363 (2006)

▼ Examples of finite complex molecular systems experiencing phase transitions.



## Turbulent dynamo and Earth magnetic field

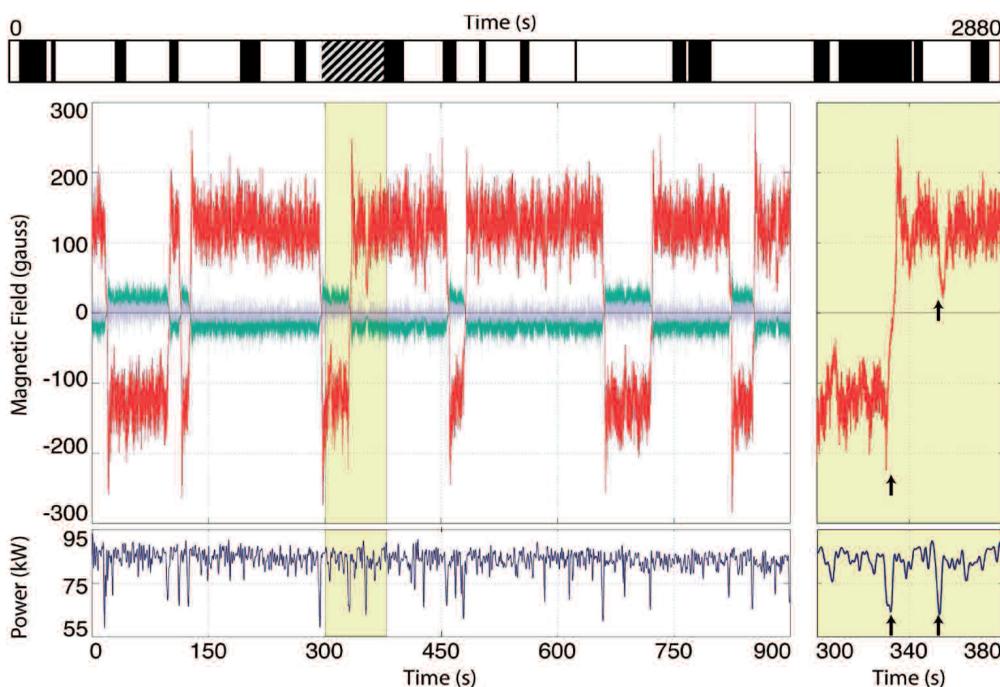
The Earth's magnetic field is aligned roughly along the rotation axis and has an approximate dipole shape. One of its most striking features, revealed by paleomagnetic studies, is the observation of irregular reversals of its polarity. Duration between reversals is on average a few hundred thousand years but is widely distributed. Reversals take on average a few thousand years. The origin of these time scales as well as the geometry of the field during a reversal are still matters of debate.

Researchers of the VKS collaboration which involves the Atomic Energy Commission (CEA), the National Center for Scientific Research (CNRS) and Ecole Normale Supérieure (ENS) institutes in Lyon and Paris, report the first observation of reversals of a magnetic field self-generated in a turbulent flow by the dynamo effect, a process believed to be at the origin

of the magnetic fields of planets and stars. The flow is driven in a cylindrical tank, filled with 160 l of liquid sodium, by rotating two iron discs fitted with blades and placed at each end of the tank. A stationary magnetic field is created when the discs are rotated in opposite directions faster than 17 Hz. When the disks are rotated at different speeds, thus generating some kind of globally rotating flow component, the magnetic field reverses at irregular time intervals (see Figure). A hierarchy of time scales similar to the Earth's magnetic field is observed: the duration of the steady phases is widely distributed, but is always much longer than the time needed to switch polarity. In this regime, the three components of the field shrink to zero and then grow again with opposite polarity. In addition to reversals, excursions are observed (the magnetic field first decays

and then grows again with its direction unchanged). Both coincide with minima of the mechanical power driving the flow because Ohmic dissipation decreases. However, at different rotation speeds, the magnetic field can also reverse pseudo-periodically by rotating in space without noticeable modification of power. These different large scale dynamics of the magnetic field generated by strongly turbulent flows in this experiment, shed light on similar features that are observed in the Earth and stellar dynamos. ■

M. Berhanu, R. Monchaux, S. Fauve, N. Mordant, F. Pétrélis, A. Chiffaudel, F. Daviaud, B. Dubrulle, L. Marié, F. Ravelet, M. Bourgoin, Ph. Odier, J.-F. Pinton, R. Volk, "Magnetic field reversals in an experimental turbulent dynamo", *Europhys. Lett.* **77**, 59001 (2007).



◀ Magnetic field measured inside the flow vessel.

(Main): Time evolution of all three magnetic field components. The main component (red) is the azimuthal one. Note that all components decay to zero at a reversal. The bottom graph shows synchronous recordings of the power driving the flow.

(Right): detail of the time series of the main magnetic field and simultaneous power consumption (arrows mark the synchronous events).

(Top): Chronos of the magnetic field orientation, white for a positive direction, black for the negative direction, for 2 successive recordings 900 and 1800 seconds long (separated by the shaded area, the first sequence corresponds to the main graph). In this regime, the flow is driven with counter-rotating disks at frequencies  $F_1 = 16$  Hz and  $F_2 = 22$  Hz.

## Errata: directory published in 38/1

Some errors slipped into the directory published in number 38/1.

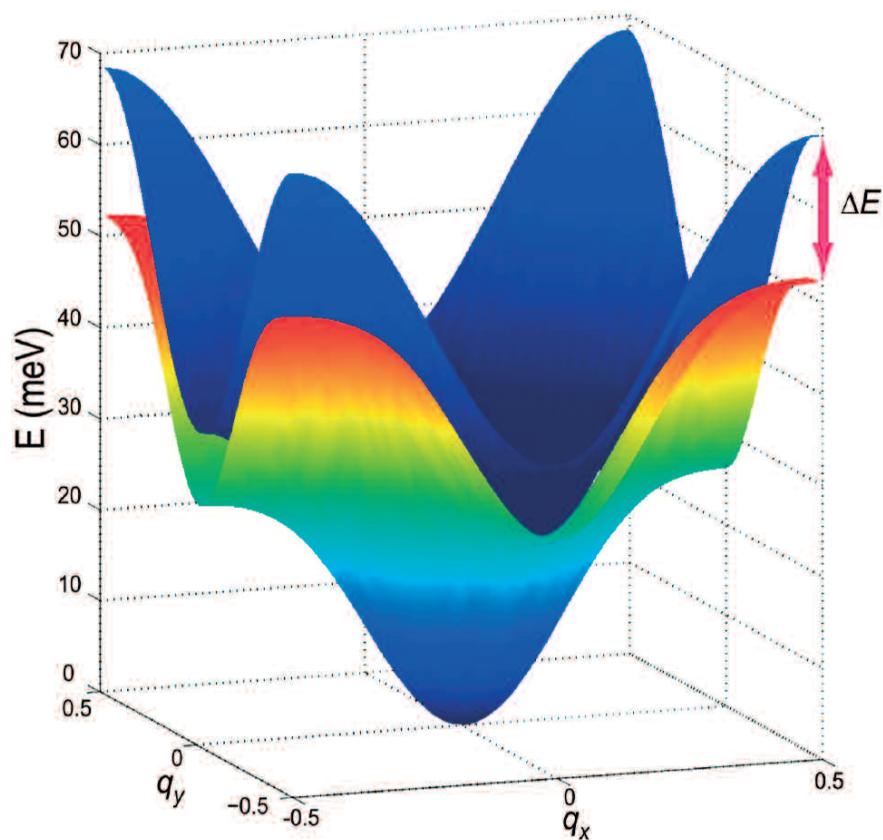
Please excuse us for these mistakes. For this reason we publish again the directory in this issue (see pages 31-32).

The complete directory is also online at [www.eps.org/directory](http://www.eps.org/directory)

## Magnons in manganites

Doped manganese oxides (manganites) are of interest not only because they are a testing ground of the classical double-exchange interaction mechanism for the observed “colossal” magnetoresistance (CMR), but also because they exhibit an extraordinary arena of emergent phenomena. It is believed that the richness of their properties results from the multitude of competing ground states — the equilibrium between phases is very subtle and small perturbations may induce a large response. The fundamental physics behind these emergent phenomena is related to the complexity which is associated with a strong interplay between electron charge, spin, orbital, and crystal lattice.

The metallic ground state associated with the ferromagnetic order in doped manganites was originally understood by the double-exchange interaction model, which has been recognized as an essential ingredient for the coupled ferromagnetic metallic-to-paramagnetic insulator transition as well as the CMR effect. However, the nature of the ferromagnetic-metallic ground state is still not understood. Especially, as focused on in this review, the spin dynamics in the ferromagnetic metallic manganites is by *no means conventional*. The unconventional behaviour of spin dynamics in ferromagnetic manganites is revealed by the deviation of the dispersion (as shown in the Figure observed from a single crystal of  $\text{La}_{0.7}\text{Ca}_{0.7}\text{MnO}_3$ ), the linewidth and the long-wavelength stiffness of magnons from the expectations of the simple double-exchange model. Based upon the fact that a strong interplay exists between different degrees of



▲ Inelastic neutron-scattering-measured ferromagnetic magnon excitation energy of a prototype CMR single crystal ( $\text{La}_{0.7}\text{Ca}_{0.7}\text{MnO}_3$ ) plotted as a function of momentum  $q_x$  and  $q_y$  in the momentum space (lower sheet) with a large Brillouin zone boundary ( $q_x, q_y = \pm 0.5$ ) deviation (indicated by the arrow) from the expected values (upper sheet) from the simple double-exchange model.

freedom and their excitations, several theoretical approaches beyond the simple double-exchange model have been attempted, including those considering magnon-phonon coupling, effects of electron-electron correlation, orbital fluctuations and local phase inhomogeneities. Yet it is fair to conclude that none of the prevailing models can account for the observed magnon behaviour. Tailoring these different inter- actions between charge,

spin, orbital, and lattice degrees of freedom for an understanding of their effects on spin dynamics should be the main challenge. ■

J. Zhang, F. Ye, H. Sha, P. Dai, J.A. Fernandez-Baca, and E.W. Plummer, “Magnons in Ferromagnetic Metallic Manganites”, Special issue *J. Phys. Condensed Matter on Half-metallic ferromagnets* (2007)

## Observation of “dark” electronic states

Most of our knowledge of structural and dynamical properties of atoms and molecules is provided by absorption or emission of light. However some transitions between electronic states of these building blocks of matter are optically forbidden and therefore inaccessible to light. These states, known as “dark states” in optical jargon, can be excited in electron impact experiments. This peculiarity of electron impact experiments is well known and is exploited in electron

energy-loss experiments by either reducing the kinetic energy of the incident beam or selecting collisions which involve a large momentum transfer from the incident electron to the target molecules. In the experiments by Feyer et al. this property has been combined with the selectivity of a coincidence technique in order to isolate for the first time the non-radiative decay spectrum of the inner-shell triplet excited state in CO, populated from the ground state of the

molecule via a dipole forbidden transition. In the experiment an electron beam of 600 eV crossed an effusive CO beam. Scattered electrons, which suffered an energy loss equal to the excitation energy of the  $\text{C } 1s \rightarrow 2\pi^* \text{II}$  transition, and autoionization electrons, ejected in the decay of this inner-shell excited state, were detected by ten independent hemispherical analyzers set in a plane perpendicular to the incident beam (see Figure). An *ab initio* multiconfiguration

## An experimental Bullard–von Kármán dynamo

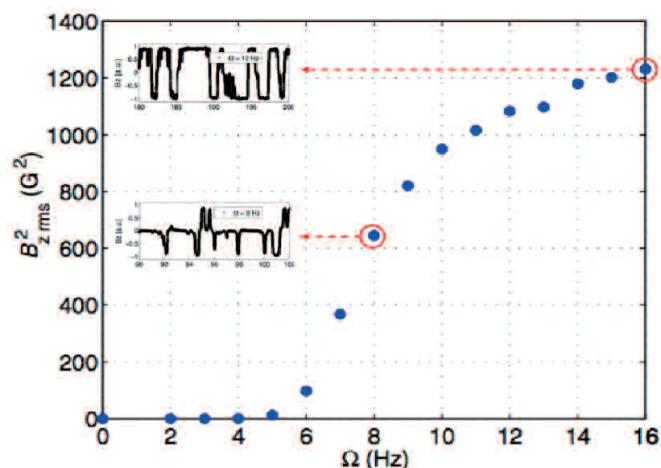
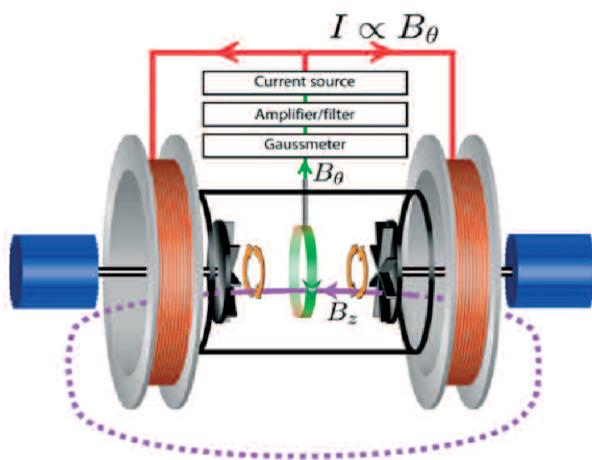
The dynamo effect is believed to be at the origin of the magnetic field of planets and stars. In this process, a fraction of the kinetic energy of motion of an electrically conducting fluid (liquid iron in the case of the Earth core) is converted into magnetic energy. It is a non-linear instability that occurs above a threshold, *i.e.* when the motion of the fluid is so vigorous that the stretching of magnetic field lines overcomes the Joule (resistive) dissipation. Not all fluid motions are appropriate, but some flows presenting helicity ( $\alpha$ -effect) or differential rotation ( $\Omega$ -effect) have been shown to be able to sustain a magnetic field. Homogeneous fluid dynamos have been realized in the laboratory. Most

recently, the VKS experiment in France has reported the first evidence of a fully turbulent dynamo. These experiments require the use of large sodium facilities. By contrast, we propose here a light and versatile dynamo experiment (see Figure) combining the idea of a Bullard dynamo and the use of a turbulent flow of liquid gallium. Using an external feedback, the setup mimics an alpha-omega dynamo (a model commonly used in astrophysics) in which the flow turbulence is fully included and has a leading role. Several important features are observed: intermittent “on-off” dynamics with magnetic bursts near threshold, and irregular magnetic field reversals far beyond threshold.

The time for a reversal is short compared to the magnetic diffusion time of the system (as is the case for the Earth’s magnetic reversals).

The versatility of the present experiment allows the study of other dynamos and gives an experimental framework for further investigations on the role of large scale fluctuations on the dynamo instability, the generic features of bifurcations in the presence of noise and an extension to phenomena such as stochastic resonance. ■

M. Bourgoin, . Volk, N. Plihon, P. Augier, P. Odier and J.-F. Pinton,  
“An experimental Bullard–von Kármán dynamo”, *New J. Phys.* **8** 329 (2006)

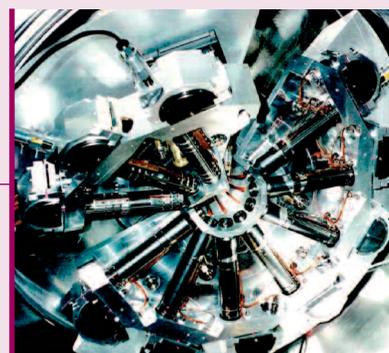


▲ **Left:** Experimental set-up: a von Kármán flow of liquid gallium is generated in a cylindrical vessel between two counter-rotating disks driven by two AC-motors. The differential rotation advects and stretches an axial field  $B_z$  produced by two Helmholtz coils so as to generate a toroidal component  $B_\theta$ . The amplitude of  $B_\theta$  is then used to drive the power source which generates the current in the coils, which closes the dynamo feedback loop. **Right:** The main figure shows the evolution of the variance of the time fluctuations of the axial magnetic field as the disks’ counter-rotation rate  $\Omega$  is increased (bifurcation diagram). The insets show two time series of the magnetic field near threshold (8Hz) where an intermittent “on-off” dynamic is observed and far above threshold (16Hz) where a fully developed reversing regime is observed.

and multi-centre calculation then allowed the assignment of the spectral features to the various transitions leading to the final  $CO^+$  doublet and quartet states and a comparison with the decay spectrum of the  $(C\ 1s^{-1}\ 2\pi)\ ^1\Pi$  excited state, populated by a dipole allowed transition. This work shows how electron beams and novel experimental techniques shed light on a basic, but still unexplored process like the decay spectrum of “dark states” of molecules. ■

V. Feyer, P. Bolognesi, M. Coreno, K. C. Prince, I. Avaldi, B. Jancik and V. Carravetta,  
“The decay of  $C\ 1s \rightarrow 2\pi\ ^3\Pi$  inner shell excited state of  $CO$ ”, *J. Phys. B* **40**, F35 (2007)

► The electron–electron multi-coincidence experimental set-up. The ten hemispherical electron analyzers are mounted on two frames. The three analyzers on the small frame were used to detect the scattered electrons, and the other seven to detect the auto-ionization electrons.



## First events in the OPERA experiment

Several key experiments conducted in the last decades with atmospheric and solar neutrinos, as well as with artificial neutrinos from nuclear reactors and particle accelerators, have contributed to our present understanding of neutrino mixing and oscillations, a quantum mechanical process that makes it possible for neutrinos produced with a given flavor (electron-, muon- or tau- neutrinos) to appear later as neutrinos of a different flavor. This process can only occur if neutrinos have a mass, even if very tiny, as the experiments indicate. However, the direct appearance of a different neutrino flavor is still an important open issue, since nobody has so far directly

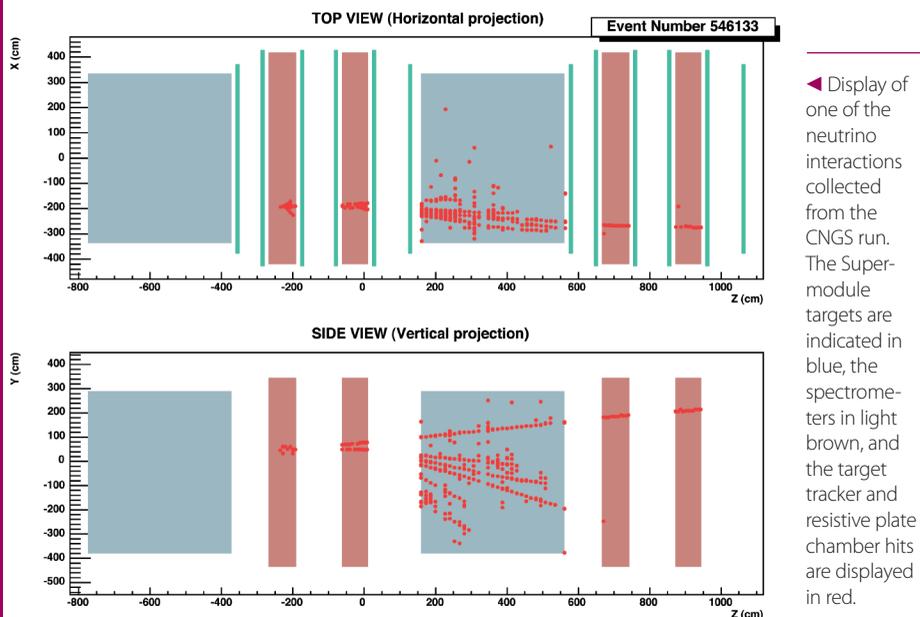
detected a different flavor appearing from the oscillation process. For this purpose, long-baseline accelerator neutrino beams can be used to probe the atmospheric neutrino signal and confirm the preferred solution of muon- to tau-neutrino oscillations. One of the main objectives of the OPERA experiment that exploits the long (730 km) baseline CNGS neutrino beam from CERN in Geneva to the Gran Sasso Laboratory (LNGS) in central Italy is to perform such an appearance experiment.

The identification of the occurrence of muon- to tau-neutrino oscillations requires the detection with high efficiency and low background of the

short-lived tau lepton (which typically has less than a mm flight path). The tau is identified by the measurement of its characteristic decay topologies, in one prong (electron, muon or hadron) or in three-prongs. Neutrino interactions are measured with a large-mass (almost 1500 tons) sampling-calorimeter made of 1 mm thick lead plates (absorber material) inter-spaced with thin nuclear emulsion films (high-accuracy tracking devices with micrometric space resolution). The sampling calorimeter is subdivided into 160000 elementary cells called bricks.

In August 2006 a first test run with CNGS neutrinos was successfully conducted and has been reported. A first sample of neutrino events, induced by neutrinos traveling under the Earth, from CERN to LNGS, was collected by the OPERA electronic detectors; their number was statistically consistent with the integrated neutrino beam intensity (see Figure). A first analysis of the events has proven that both the CNGS neutrino facility and the OPERA experiment behave as expected. This is an important milestone on the road to the full construction of the detector and of its future physics runs. The filling of the detector with bricks is proceeding and the physics runs will start in 2007. ■

R. Acquafredda + 220 co-authors, "First events from the CNGS neutrino beam detected in the OPERA experiment", *New J. Phys.* **8** 303 (2006)



## Imaging nuclear wave-packets on the sub-femtosecond scale

The ultrafast molecular dynamics in strong fields is one of the challenges in contemporary molecular physics. The molecule exhibits three timescales, the fast electronic motion (attosecond scale), the vibrational (femtosecond scale) and the rotational (picosecond scale) nuclear motions. The vibrational nuclear motion has received a constant attention with the possibility of mapping the nuclear wave-packet by combining a femtosecond (fs) pump-probe arrangement with the so called Coulomb explosion (CE) imaging technique. In general this technique involves two infrared (IR) fs pulses; the

first (the pump) prepares a coherent superposition of vibrational states of a molecular ion via fast ionisation of the parent molecule; the second (the probe) ionises the molecular ion. The CE imaging technique has been shown to be very efficient but the duration and intensity of the probe put some limitations on the temporal/spectral resolution.

In their theoretical work, Barmaki and Bachau propose to take advantage of the recent progress realised in the domain of high-order harmonic generation (HOHG) and to use an attosecond (as) XUV pulse, synchronized with the IR

pump radiation, as a probe. Let us consider the case of the H<sub>2</sub> molecule in its fundamental state; it is quickly ionised (at t=0) by the strong IR pulse. The XUV probe pulse has a duration of 500 as and a wavelength centred at ~15.2 nm; it ionises the H<sub>2</sub><sup>+</sup> vibrational wave-packet through one-photon absorption. The Figure shows the proton kinetic energy distributions, the probe arriving at different time delays (from the right to the left; t=0, 1.2, 2.4, 4.8, 7.2 fs). It is easy to reconstruct (with the help of the Coulomb law  $R \propto 1/E$ ) the evolution of the wave-packet while it expands. Pump-

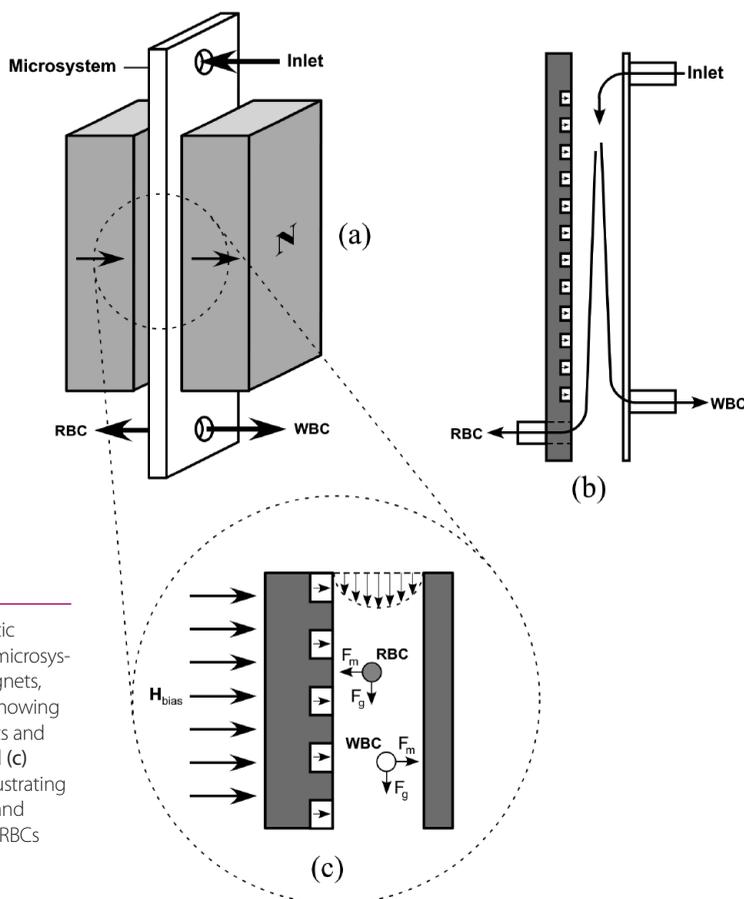
## Easier blood cell divorce

A new method has been proposed for separating red and white blood cells using a combination of magnetic and microfluidic technology. Blood cell separation is routinely performed for diagnostic purposes each time a sample of blood is taken from a patient. Currently, the most common way to separate red and white blood cells is by spinning the sample at high speeds in a centrifuge, which takes approximately 20 minutes. Dr. Edward Furlani of the University at Buffalo has proposed a cell separation method that requires much smaller samples and enables much faster separation, on the order of a few minutes. Dr. Furlani's method, which has yet to be realized in the laboratory, involves the use of a microsystem that consists of an array of magnetic elements embedded next to a vertical microfluidic channel (see Figure). The magnetic elements are fractions of a mm wide and the entire device would be only a few cm in length. During operation, a small sample of venous (deoxygenated) blood would be injected at the top of the channel, and an external magnetic field would be applied to the system, which effectively turns the embedded magnetic elements into small magnets. As blood flows through the channel, the blood cells experience a magnetic force that moves them according to their magnetic properties; this process is called magnetophoresis. In whole blood, deoxygenated red blood cells and white blood cells have opposite magnetic properties; the former are para-

magnetic while the later are diamagnetic. Dr. Furlani has modeled blood cell transport through the microsystem and has found that deoxygenated red blood cells would be attracted towards the magnets while white blood cells would be repelled, sufficiently so to enable efficient separation. According to Dr. Furlani,

his technique could be used to create portable, low-cost and energy efficient microdevices for rapidly processing small volumes of blood. ■

E. P. Furlani, "Magnetophoretic separation of blood cells at the micro-scale", *J. Phys. D: Appl. Phys.* **40**, 1313 (2007)

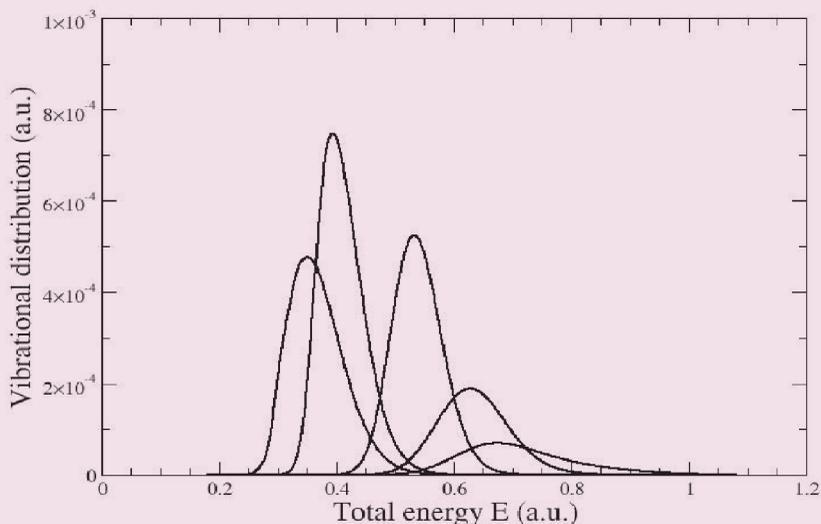


► Magnetophoretic microsystem: (a) microsystem with bias magnets, (b) cross-section showing magnetic elements and microchannel, and (c) magnified view illustrating separation of red and white blood cells (RBCs and WBCs).

probe techniques involving HOHG open the way to exploring the *coherent motion of nuclear wave-packets* at fs and sub-fs time scales. ■

S Barmaki and H Bachau, "Coulomb explosion of  $H_2^+$  wave packet in ultrashort XUV laser fields", *J. Phys. B* **40**, 463 (2007)

► Vibrational distribution of the protons for delay time  $\Delta T=0, 50, 100, 200$  and  $300$  a.u. (from the right to the left). Total pulse duration of  $T=20.94$  a.u., photon energy  $\omega=3$  a.u. and peak intensity  $I=10^{14} \text{W/cm}^2$ .



# Mapping spin structures on the atomic scale

[DOI: 10.1051/EPN:2007004]

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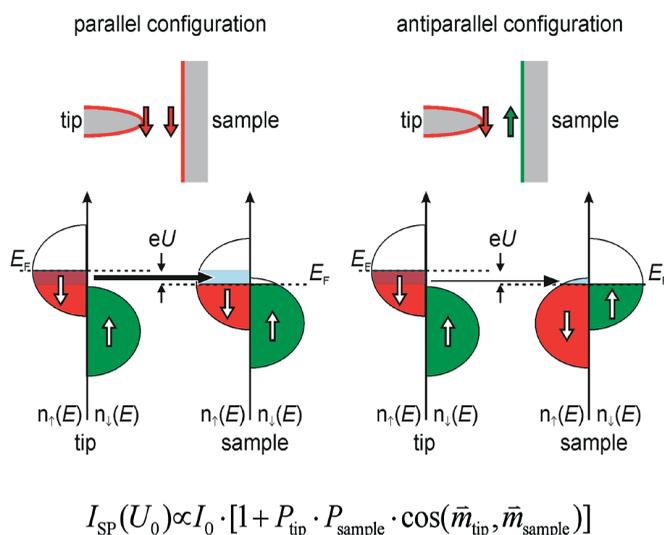
Email: wiesendanger@physnet.uni-hamburg.de • Web: www.nanoscience.de

A fundamental understanding of magnetic and spin-dependent phenomena requires the determination of spin structures and spin excitations down to the atomic scale. The direct visualization of atomic-scale spin structures [1-4] has first been accomplished for magnetic metals by combining the atomic resolution capability of Scanning Tunnelling Microscopy (STM) [5,6] with spin sensitivity, based on vacuum tunnelling of spin-polarized electrons [7]. The resulting technique, Spin-Polarized Scanning Tunnelling Microscopy (SP-STM), nowadays provides unprecedented insight into collinear and non-collinear spin structures at surfaces of magnetic nanostructures and has already led to the discovery of new types of magnetic order at the nanoscale [8]. More recently, the detection of spin-dependent exchange and correlation forces has allowed a first direct real-space observation of spin structures at surfaces of antiferromagnetic insulators [9]. This new type of scanning probe microscopy, called Magnetic Exchange Force Microscopy (MExFM), provides a powerful new tool to investigate different types of spin-spin interactions based on direct-, super-, or RKKY-type exchange down to the atomic level. By combining SP-STM with inelastic electron tunnelling spectroscopy [10] or by performing MExFM together with high-precision measurements of damping forces [9] localized or confined spin excitations in magnetic systems of reduced dimensions now become experimentally accessible.

## Principles of Spin-Polarized Scanning Tunnelling Microscopy (SP-STM) and Spectroscopy (SP-STs)

The technique of SP-STM is based on vacuum tunnelling of spin-polarized electrons as can be observed in STM-type tunnel junctions involving a magnetic tip and a magnetic sample (Fig. 1). In this case, the tunnelling current does not only depend on the tip-surface separation and the applied bias voltage between tip and sample, but also on the spin polarization of the electronic states near the Fermi level of both electrodes as well as on the relative orientation of the local magnetization of the sample and the magnetic moment at the tip apex. Early experiments based on planar tunnel junctions involving magnetic electrodes have been performed by Jullière in the mid-seventies [11]. The invention of the STM by G. Binnig and H. Rohrer [5] allowed the replacement of the ill-defined tunnel barrier of planar tunnel junctions by a well defined vacuum barrier and the replacement of one of the planar electrodes by a freely movable and positionable probe tip. Magnetic tips have first been employed in scanning probe microscopy to perform spatially resolved measurements of magnetic dipole forces [12]. The corresponding technique, Magnetic Force Microscopy (MFM), has become a routine method for magnetic domain imaging [13]. However, the spatial resolution of MFM is limited to 10 - 20 nm due to the long-range nature of the magnetic dipole forces [6]. In order to improve the spatial resolution of magnetic-sensitive scanning probe microscopy down to the atomic scale, two different approaches have been proposed at the end of the eighties: either to measure spin-dependent tunnelling currents making use of the strong exponential dependence of the tunnelling current on the tip-surface distance in order to combine atomic- with spin-resolution, or to measure spin-dependent exchange and correlation forces at very small distances between a magnetic probe tip and a magnetic sample based on the atomic force microscopy (AFM) technique [14].

The first successful observation of vacuum tunnelling of spin-polarized electrons in an STM experiment was made in 1990 [7] using a highly spin-polarized CrO<sub>2</sub> thin film probe tip and an antiferromagnetic Cr(001) sample in order to exclude a disturbing influence of superimposed magnetic dipole interactions. In these early SP-STM experiments, the constant-current mode of operation was employed where spin-polarized tunnelling current effects showed up as apparent height differences in constant-current STM contours. This mode of operation has turned out to be useful for atomic-scale SP-STM studies of surface spin configurations, as has been shown by resolving the spin structure at surfaces of ferrimagnetic oxides [1], two-dimensional antiferromagnetic metal layers [2-4] and antiferromagnetic nitrides [15]. For nanoscale magnetic domain imaging the spectroscopic mode of SP-STM operation, introduced in 1998 [16], was found to be superior compared to the constant-current mode, particular with respect to a clear separation between



▲ Fig. 1: Principle of Spin-Polarized Scanning Tunnelling Microscopy (SP-STM): the spin-polarized tunnelling current flowing between a magnetic tip and a magnetic sample depends on the relative alignment of the local magnetization of tip and sample as well as on the spin polarization of electronic states of tip and sample contributing to the tunnelling current.

topographic, electronic, and magnetic contrast effects [17,18]. In the spectroscopic mode of SP-STM the spin-resolved differential tunnelling conductance  $dI/dU$  is measured with spatial resolution. The bias voltage applied between the magnetic tip and the magnetic sample is chosen in such a way that tunnelling into or out of a highly spin-polarized electronic state leads to a high spin contrast image. The advances which came along with the spectroscopic mode of SP-STM (called SP-STs) operation is nicely demonstrated by experiments revealing the magnetic domain structure of rare-earth metal films, such as Dy(0001) epitaxially grown on W(110) single crystal substrates [19].

### Ultra-high resolution magnetic domain imaging by SP-STs

In Fig. 2 simultaneously recorded topographic and magnetic maps of a Dy(0001) thin film are presented. While the topographic STM image (a) reveals a relatively smooth surface structure with atomically flat terraces together with some surface steps and several dislocations, the SP-STs image (b) clearly shows the magnetic domains with very sharp transitions (magnetic domain walls) between them. Since the magnetic anisotropy is in the plane of the Dy film, an in-plane magnetized thin film probe tip has been used in order to achieve a high spin contrast. Additionally, the applied sample bias voltage has been chosen in such a way that highly spin-polarized electronic states are involved in tunnelling. The observed six different contrast levels in the magnetic SP-STs image result from the six equivalent in-plane directions of the local sample magnetization reflecting the six-fold symmetry of the underlying hexagonal crystal lattice structure of the Dy film. For a given tip magnetization direction (quantization axis) this leads to six different projections (mathematically described by the cosine-dependence of the spin-polarized tunnelling current on the angle between the tip and sample magnetization directions, see

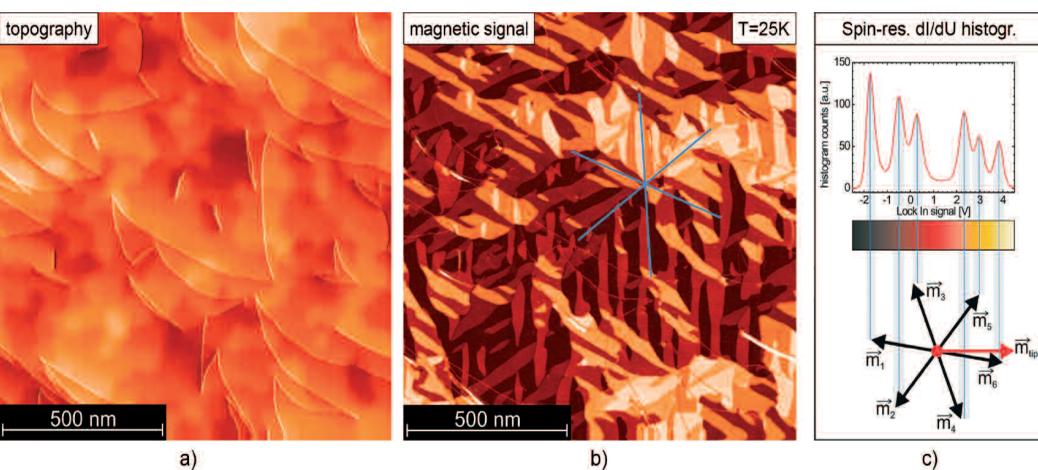
Fig. 1) which can clearly be identified in the histogram of the measured values of the spin-resolved  $dI/dU$  signal across the whole image (see Fig. 2c). The very sharp transitions between the observed magnetic domains result from the relatively high magnetic anisotropy of the Dy film leading to very narrow domain walls of only 2 - 3 nm in width. For single atomic layers of Fe on W(110) substrates even atomically sharp domain walls have been revealed by SP-STs [18]. In this case, the magnetic anisotropy of the single atomic layer of Fe on W(110) is much larger than for bulk Fe where domain wall widths are typically on the order of a hundred nanometers.

It should be emphasized that a reliable *quantitative* determination of magnetic domain wall widths requires the use of magnetic stray field-free tips in scanning probe microscopy. This has always been a severe problem in MFM studies of magnetic domain walls. However, the problem can be solved based on the SP-STM method by introducing antiferromagnetically coated probe tips [20,21] which still exhibit spin-polarized electronic states for tunnelling but are strayfield-free. Therefore, they do not affect the position or the measured width of magnetic domain walls or magnetic vortices [21]. Moreover, it has been demonstrated that even a non-magnetic probe tip may be able to image domain walls since the local electronic structure is modified within the domain wall due to the local change of the magnetization direction and the accompanied change of the spin-orbit coupling between electronic states [22,23].

To summarize this part, SP-STs allows us to enter a new regime of magnetic domain and domain wall observation at sub-nanometer scale spatial resolution which is not accessible by any other magnetic imaging technique up to now.

### Spin-resolved electronic structure at the nanoscale

The real value of the STM technique is not just its high spatial resolution but is also that the combination with tunnelling



◀ **Fig. 2:** Application of SP-STs towards magnetic domain imaging with sub-nanoscale spatial resolution: a thin Dy(0001) film grown epitaxially on a W(110) substrate exhibits a domain structure with six different in-plane orientations of the local magnetization. The six different contrast values in the SP-STM image result from the six different projections of the local sample magnetization onto the local magnetization direction of the probe tip (quantization axis). The relatively high magnetic anisotropy of Dy leads to narrow magnetic domain walls of typically 2 - 3 nm width [22].

spectroscopy provides access to the spatial distribution of electronic states down to the atomic level [5]. Most importantly, this type of atomic-resolution spectroscopy can be performed at low energy scales which are relevant to the investigation of quantum phenomena in nanostructures, in addition to providing a *non-destructive* imaging method. The combined observation of atomic-scale surface topography and spatial distribution of the electronic states by Scanning Tunnelling Spectroscopy (STS) is illustrated in Fig. 3a. Nanoscale Co islands of triangular shape and two atomic layers height have been prepared on a Cu(111) surface which exhibits a well known Shockley-type surface state. The surface state electrons scatter at the interface of the Co islands with the Cu substrate and the reflected electron waves interfere with the incoming waves, resulting in a standing wave pattern near the Co island edges. Surface state electrons are also scattered at individual Co atoms giving rise to circular-symmetric (*s*-type) scattering states characteristic of free-electron behaviour. On top of the topographically flat Co islands electronic modulations are observed which result from the quantum mechanical lateral confinement of the electrons within the triangular shaped Co islands. While conventional STS methods have already widely been used to study such phenomena on many different surfaces, only SP-STs allows us to address questions related to the magnetic state of nanoscale islands [24], the spin-dependence of the electronic confinement states [25], and the spin dependence of the electronic scattering at nanoscale interfaces or at individual adatoms [26]. Fig. 3b shows examples of four different SP-STs maps obtained at four different energies (sample bias voltages), revealing the spatial distribution of the corresponding spin-polarized electronic states within the single-domain Co islands below and above the onset of the Cu surface state. The particular energies have been selected in such a way that the corresponding spin asymmetry of the tunnelling current and therefore the spin contrast in the SP-STs image is high. Therefore, the magnetic state of the Co islands with a magnetic

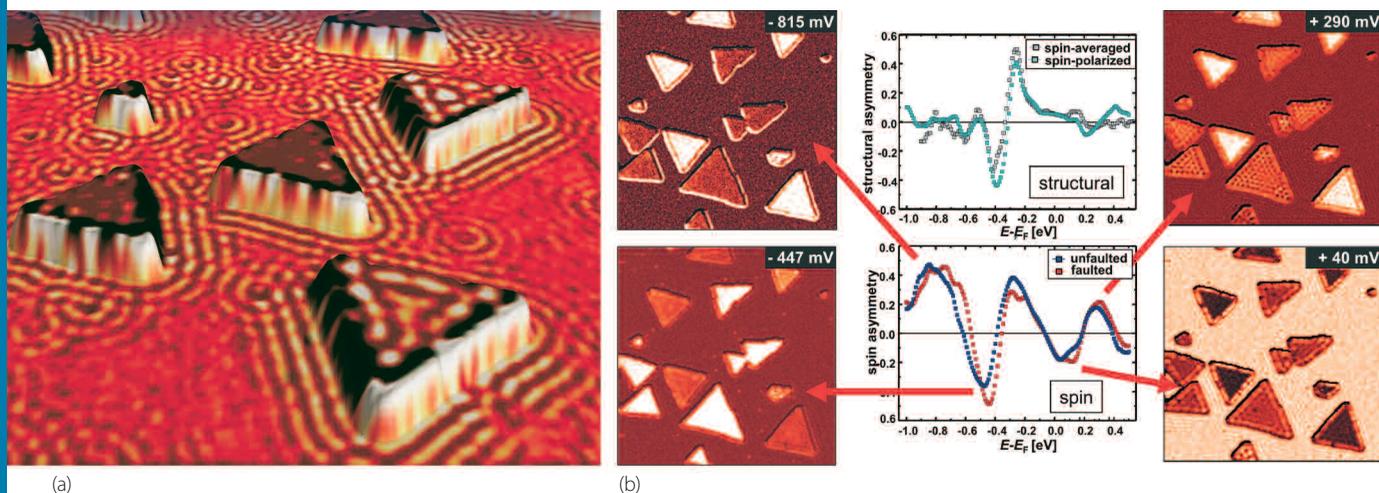
out-of-plane anisotropy (either with an upward or a downward magnetization direction) clearly shows up as bright or dark contrast. At positive sample bias voltages the electronic modulations due to the Cu(111) surface state and due to the laterally confined states within the Co islands are nicely visible in addition. By carefully analyzing the dependence of the amplitude of these electronic modulations on the magnetization state of the respective Co islands, the spin character of the electronic confinement states can be deduced [25]. Even the spin character of one-dimensional confinement states at the rim of such nanoscale Co islands could recently be determined [25].

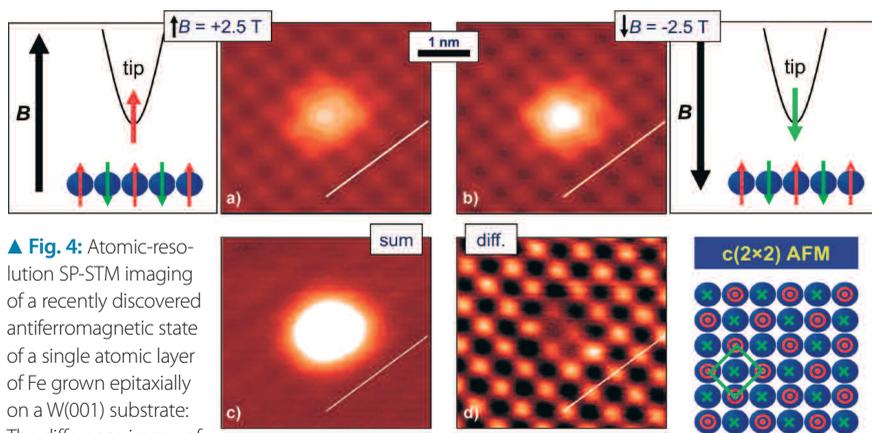
Notice that these SP-STs experiments have been performed at low temperatures (14 K) where the nanoscale Co islands are in a ferromagnetic state. At higher temperatures thermal fluctuations may lead to a superparamagnetic behaviour which can be studied by time-dependent SP-STs experiments [27].

### Discovery of antiferromagnetic order in Fe monolayers by atomic-resolution SP-STs

Atomic-resolution mapping of surface spin structures has been a dream for a long time which became a reality for electrically conducting materials by the combination of the STM technique with the development of appropriate spin-polarized probes. A first step towards atomic-scale SP-STs studies was made by resolving the different *magnitude* of the magnetic moments of octahedrally coordinated  $\text{Fe}^{3+}$  and  $\text{Fe}^{2+}$  sites at the  $\text{Fe}_3\text{O}_4(001)$  surface [1]. A few years later the different *orientation* of the magnetic moments of chemically identical Mn atoms within an antiferromagnetic Mn monolayer prepared on a W(110) substrate was directly observed in real space by SP-STs [2]. Another atomic-resolution SP-STs investigation was reported for a  $\text{Mn}_3\text{N}_2(010)$  surface by Yang et al. [15]. For all these early SP-STs studies revealing the atomic spin configuration, the constant-current mode of operation was employed, as introduced in 1990 [7]. However, atomic resolution can also be obtained in the spectroscopic mode in which the spin-resolved

▼ **Fig. 3:** Nanoscale Co islands of two atomic layers height grown on a Cu(111) substrate: (a) Perspective-view STS image exhibiting simultaneously the sample topography and the electronic standing wave patterns on the Cu (111) surface as well as the quantum mechanical electronic confinement states within the Co islands. (b) Top-view SP-STs images of the Co-islands on Cu(111) obtained at different samples biases corresponding to energies below or above the onset of the Cu(111) surface state. The sample bias voltages have been chosen in such a way that the energy-dependent spin asymmetry of the tunnel junction and therefore the magnetic contrast in the SP-STs images becomes large. Notice that the spin asymmetry not only varies in magnitude but even changes sign as a function of energy. At zero-crossings of the spin asymmetry curve no magnetic contrast is obtained [27,28].





▲ **Fig. 4:** Atomic-resolution SP-STM imaging of a recently discovered antiferromagnetic state of a single atomic layer of Fe grown epitaxially on a W(001) substrate: The difference image of the two data sets (a) and (b) obtained with two oppositely magnetized probe tips results in a magnetic contrast image (d) which reveals for the first time a direct real-space view of Néel-type order on a square lattice [3]. The sum image of (a) and (b) results in a topographic map (c) showing an atomic adsorbate which was used to perform the registry between the two images (a) and (b).

differential tunnelling conductance signal  $dI/dU$  is measured with spatial resolution. An example is presented in Fig. 4 where atomic resolution images of a recently discovered antiferromagnetic ground state of a single atomic layer of Fe on a W(001) substrate [3] are presented. At first, a SP-STs image was obtained with a Fe-coated probe tip being magnetized in an external out-of-plane magnetic field of +2.5 T. A second SP-STs data set was recorded at the same sample location with the same tip but now being magnetized in the opposite direction using an external magnetic field of -2.5 T. By calculating the difference image of these two data sets, the Néel-type spin order on the square (001) lattice can clearly be revealed whereas the sum image represents the surface topography with an atomic adsorbate which was used to perform the registry between the two images measured with oppositely magnetized probe tips. The experimentally determined out-of-plane magnetic anisotropy of the antiferromagnetic Fe monolayer on W(001) has been confirmed by density-functional theory (DFT) calculations taking spin-orbit coupling into account [3].

Since the reproducibility of SP-STM and SP-STs imaging is nowadays at the same level as for conventional STM experiments we can take a series of atomic-resolution SP-STM data sets at varying sample locations and put them together in order to reveal the spin ordering in the presence of defects (vacancies or adsorbates) and nanoscale islands (Fig. 5a). Interestingly, the perfect Néel-type spin order is maintained right up to the point-defect sites and step edges. It has proven to be very difficult to find domain walls in the antiferromagnetic Fe monolayer. Only in rare cases where two extended defects are quite close in space were we able to find and study antiferromagnetic domain walls [4]. A detailed view of such a domain wall with atomic and spin resolution is

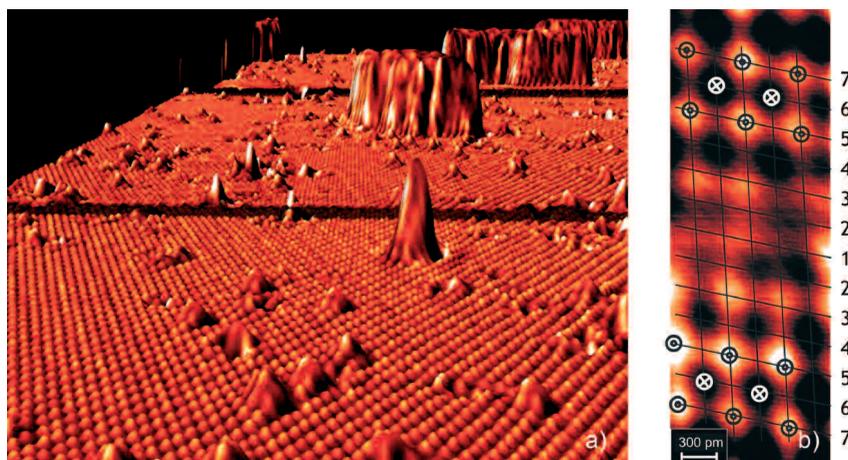
presented in Fig. 5b. The domain wall width only amounts to 6 - 8 atomic rows which has been confirmed by Monte Carlo simulations [4].

The first direct real-space view of non-collinear spin structures as present within the domain wall region of antiferromagnetic layers (Fig. 5b) has triggered several other SP-STM studies of complex spin structures, including a recently discovered mosaic-type spin structure of an Fe monolayer on Ir(111) with 15 atoms per unit cell, where 7 atoms have their spins pointing in one direction and 8 atoms have their spins pointing in the opposite direction [8]. Another interesting example is given by the recent discovery of cycloidal spin spirals in ultra-thin magnetic layers.

### Mapping atomic-scale spin structures on insulators by MExFM

While SP-STM and SP-STs methods have provided unprecedented insight into atomic spin configurations at surfaces, their application is limited to electrically conducting samples such as magnetic metal films or magnetic semiconductors. In order to reveal atomic spin structures at surfaces of insulators and to open up the exciting possibility of studying spin ordering effects with atomic resolution while going through a metal-insulator transition, we have developed the technique of Magnetic Exchange Force Microscopy (MExFM). This technique is based on the detection of short-range spin-dependent exchange and correlation forces at very small tip-sample separations (a few Angströms), in contrast to MFM where the magnetic dipole forces are probed with a ferromagnetic probe tip at a typical tip-to-surface distance of 10 - 20 nm. An important

▼ **Fig. 5:** (a) Perspective-view of several atomic-resolution SP-STM images of the antiferromagnetic monolayer of Fe on W(001) put together in order to reveal the perfect antiferromagnetic spin ordering even up to atomic-scale defects (vacancies and adsorbates) and double-layer high Fe islands. Notice the small signal strength originating from the periodic spin lattice in comparison to the signal originating from single adsorbed atoms or single-atom high steps. (b) Atomic-resolution SP-STM image of a domain wall in the antiferromagnetic Fe monolayer. The domain wall width only amounts to 6 - 8 atomic rows [4].



starting point for achieving the challenging goal of atomic-resolution spin mapping on surfaces of insulators has been the development of non-contact atomic force microscopy (NC-AFM) with true atomic resolution [28]. Nowadays, NC-AFM allows atomically resolved studies of any material system [29], even in the case of curved surface topographies [30]. MExFM combines the possibilities of NC-AFM and atomic-scale spin resolution by making use of an atomically sharp probe tip with a very well defined spin state at its apex. Based on the knowledge gained during the development of SP-STM in preparing such tips we have recently succeeded in resolving the surface spin structure of the antiferromagnetic insulator NiO(001) [9]. Fig. 6a shows an atomic-resolution topographic NC-AFM image revealing chemical contrast between the oxygen atoms (bright sites) and the Ni atoms (dark sites) which originates from a different total charge density above O- and Ni-sites. No contrast is observed between magnetically inequivalent Ni sites, *i.e.* Ni atoms with a different orientation of their magnetic moments. By approaching the out-of-plane magnetized Fe-coated tip closer to the surface atoms, the spin-dependent exchange interaction between the rather localized Ni d-states of the sample and the Fe d-states of the tip leads to a different force or force gradient above Ni atoms with a different orientation of their magnetic moments. As a result, a superperiodicity corresponding to an antiferromagnetically ordered state of the NiO(001) surface is observed in the MExFM image (Fig. 6b). Notice that the apparent height difference between the magnetically inequivalent Ni-sites, corresponding to the different magnitude of the spin-dependent quantum-mechanical forces felt by the tip above the different Ni atoms, only amounts to 1.5 pm as can be deduced from the line section in Fig. 6b. To resolve such tiny signals, the AFM instrument has to be operated at low temperatures in order to reduce the thermal excitations of the AFM cantilever (force sensor).

To summarize, it has become possible to measure spin-dependent quantum mechanical exchange forces between a single atom at a tip apex and individual surface atoms, leading to a new type of scanning probe microscopy technique which can now resolve atomic spin structures at surfaces of any type of material system, thereby extending the range of applications of SP-STM considerably. Interestingly, it has taken more than a

hundred years after the foundations of quantum mechanics have been formulated, to be finally able to measure the spin-dependent forces between quantum objects directly. ■

### Acknowledgments

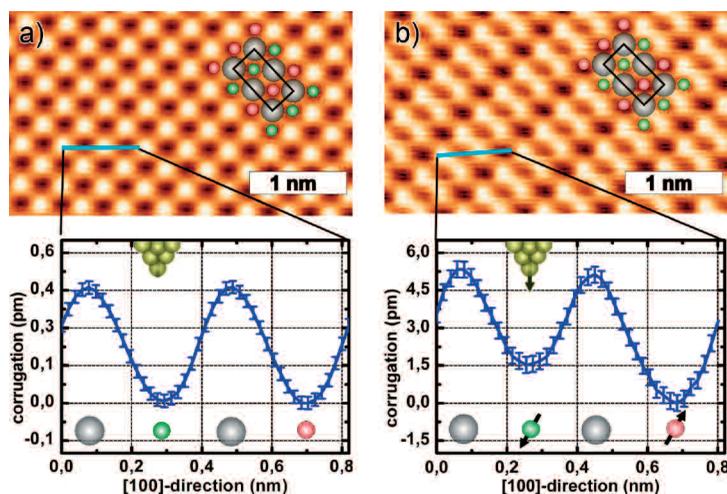
I would like to thank my coworkers and collaborators L. Berbil-Bautista, K. von Bergmann, S. Blügel, M. Bode, P. Ferriani, S. Heinze, U. Kaiser, S. Krause, A. Kubetzka, A. Lichtenstein, O. Pietzsch, A. Schwarz, and E. Vedmedenko for their contributions. Financial support from the DFG Center of Excellence SFB 668 is gratefully acknowledged.

### About the author

**Roland Wiesendanger** studied Physics at the University of Basel where he received his Ph.D. in 1987. Since 1989 he has been working towards magnetic imaging with atomic resolution. In 1993 he became full professor (C4) at the University of Hamburg where he initiated several nanoscience centers. He has already received several awards, among them the Karl Heinz Beckurts Prize, the Philip Morris Research Prize, the Gaede Prize, and the Max Auwärter Prize. He is an elected member of the German Academy Leopoldina and the Hamburg Academy of Sciences.

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◀ **Fig. 6:** (a) Atomic-resolution image of an antiferromagnetic NiO(001) surface obtained by non-contact atomic force microscopy (NC-AFM) exhibiting pure chemical contrast. The line section reveals an apparent height difference of 4.5 pm between nickel (dark) and oxygen (bright) sites. Unit cell averaging has been employed in order to improve the signal-to-noise ratio in this data set. (b) Spin-resolved image of NiO(001) with atomic resolution as obtained by Magnetic Exchange Force Microscopy (MExFM) after unit cell averaging. While the oxygen atoms reveal the same contrast throughout the image the nickel atoms with opposite spin orientations now show up with an apparent height difference of 1.5 pm. This small height difference in the MExFM image results from the magnetic exchange interaction between the magnetic atom at the tip apex and the magnetic atoms on the sample surface depending on the relative spin alignment. Notice that the spin-dependent exchange and correlation forces on the antiferromagnetic NiO surface can only be measured at very small tip-surface distances due to the localized nature of the Ni d-states in the insulating NiO sample [10].

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## Hearing the curtains [DOI: 10.1051/EPN:2007005]

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If there is one place in the house that we like to sing in, it's the bath. The reason is the unusually long reverberation time: the exponential decay of any sound is slow. It is all described by Sabine's law, which states that the typical decay time of sound in a room is proportional to the volume of the room and inversely proportional to the total area of surfaces that completely absorb the sound (like an open window would, for example).

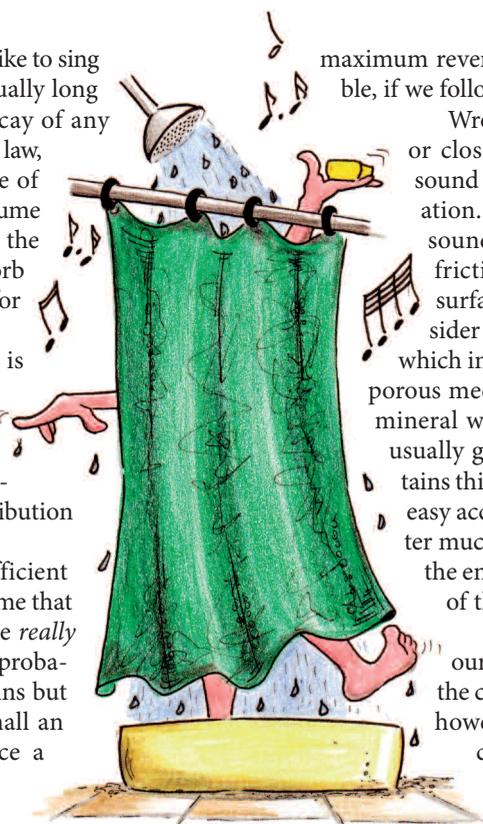
So if it comes to reverberation, the bath is pretty unique. It usually has bare walls, tiles on the floor, and little or no furniture that could absorb sound. Even our own clothing may give a much smaller contribution than usual - if it gives any contribution at all.

That leaves only the curtains as an efficient means for absorbing the sound, if we assume that we do have curtains in our bath. So if we *really* want to enjoy our own singing, we would probably be well advised *not* to close the curtains but leave them open, in order to have as small an absorbing surface as possible and hence a

maximum reverberation time. That seems very plausible, if we follow our physical intuition.

Wrong. Whether we have the curtains open or closed makes very little difference for the sound absorption, and hence for the reverberation. The reason is somewhat subtle: the sound is dissipated at surfaces indeed, by friction losses of the sound waves near the surface. But, more precisely, we have to consider the microscopic surface of the material, which includes the pores. That is the reason why porous media like thick draperies, carpets, fibrous mineral wool, glass fiber and open-cell foam are usually good sound absorbers. And for the curtains this means: as long as the sound waves have easy access to the inner surface, it does not matter much whether the curtain is spread out over the entire wall or bundled together in a corner of the room.

The conclusion therefore must be: With our eyes closed, we can't really tell whether the curtains are open or closed. We do notice, however, if they happen to be at the dry cleaner's. ■



# Carpet of magnetic colours [DOI: 10.1051/EPN:2007006]

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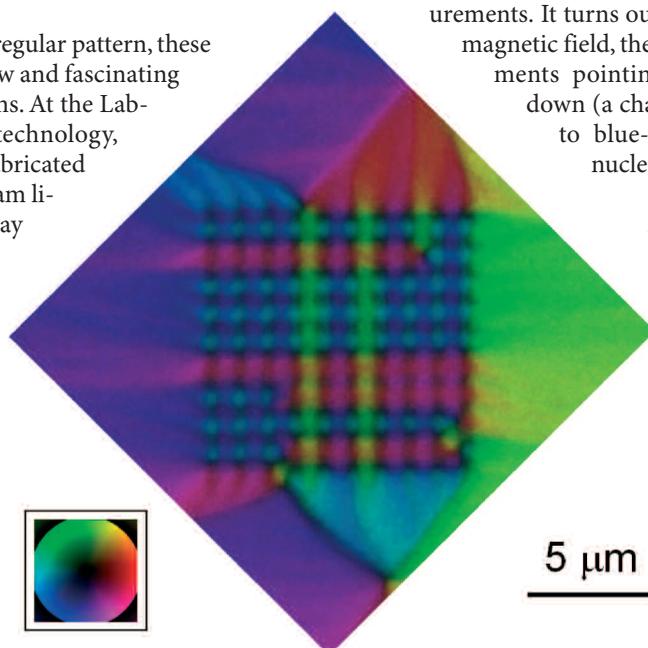
**C**OULD Néel have anticipated in 1944 that his prediction of how magnetic domains form around a cavity [1] would provide inspiration in the nanoworld to use sub-micrometer holes to engineer the properties of magnetic thin films? When Williams experimentally observed magnetic domains under an optical microscope in 1947 [1], could he have imagined the tiny length scales at which we image and identify complex magnetic structures today? The pace of development in lithography methods and imaging techniques in recent years is breathtaking, yielding new scientific discoveries and miniature devices. The opportunity to significantly reduce the lateral dimensions of thin films has led to a revolution in the area of magnetic materials, with nanoscale magnetic elements and their interaction with electric current providing novel sensor and data storage applications. In order to be able to make useful devices, we need to understand how the individual magnetic components function and, while one can perform macroscopic electrical or magnetic measurements, it is important to directly observe at the nanoscale how the magnetic moments behave.

Domains in ferromagnetic materials are regions where the magnetic moments are aligned parallel to each other. They are separated by domain walls; a region where the moments rotate from one domain orientation to the other, reminiscent of the grain boundaries separating grains with different crystal orientations in a polycrystalline material. In the mid-20<sup>th</sup> century, Néel and Williams predicted and showed that in the presence of a cavity, the magnetic moments align parallel to the cavity edges. This reduces the magnetic field emanating from the walls of the cavity, so minimising the energy of the magnetic system and resulting in a modification of the magnetic domain patterns. Using modern lithography techniques we can now produce Néel's cavities with nanoscale dimensions in ferromagnetic thin films.

Arranged very precisely in a regular pattern, these so-called antidot arrays have new and fascinating properties at reduced dimensions. At the Laboratory for Micro- and Nanotechnology, Paul Scherrer Institut we have fabricated antidot arrays using electron beam lithography to create a square array of holes in a cobalt thin film with periods down to 100 nm. We directly observed the magnetic configurations [2] employing photoemission electron microscopy (PEEM) using synchrotron radiation at the Swiss Light Source which provides magnetic information at high spatial resolution. With these observations we were able to determine how these antidot arrays influence the

magnetic moments in the layer. Specifically, the cavities dictate the orientation and position of the domain walls, resulting in periodic patterns commensurate with the hole array. The Figure shows a two dimensional map of the magnetic moments in one of the antidot arrays, here with a period of 1  $\mu\text{m}$ . At first sight, the image looks like a carpet with an intricate, unfathomable design. Taking a closer look, it is possible to identify orthogonal chains of magnetic domains, given by lines of colour running vertically (magnetic moments pointing upwards or downwards) or horizontally (magnetic moments pointing to the left or to the right).

It has been known for some time that the introduction of nanoscale antidot arrays into a magnetic thin film will significantly modify the magnetic properties, resulting in novel magnetic domain configurations and additional magnetic anisotropies [3-6]. These properties can be tuned by modifying the hole shape, size and symmetry. In particular, this changes the way in which the system switches from one magnetic state to another, in other words, how the orientation of the magnetic moments change in an applied magnetic field. An understanding of how this switching occurs, which is important for the control of new magnetic devices, can be achieved by imaging the magnetic configurations. A few images of antidot arrays have already been published [3-6], but very little has been reported about the way in which these configurations develop in a magnetic field. Our first observations with the PEEM [7] gave a hint of cooperative behaviour; we observed that the domains formed in chains, seen as lines of colour in the Figure. In a more comprehensive investigation we were able to uncover the details of switching processes [2] behind the hysteresis loops (field versus magnetisation curves) obtained from magneto-optical Kerr effect measurements. It turns out that on application of a vertical magnetic field, the switching from all magnetic moments pointing up to all moments pointing down (a change in colour from green-yellow to blue-pink in the Figure) occurs by nucleation and propagation of vertical



◀ **Fig. 1:** Magnetic Carpet; A two dimensional colour map of the magnetic configuration in a 10 nm – thick cobalt film with an array of 10 by 10 square holes (size = separation = 500 nm). Lines of colour corresponding to chains of magnetic domains can be seen: running vertically (magnetic moments pointing upwards – green/yellow, or downwards – blue/pink); or horizontally (magnetic moments pointing to the left – dark blue/light blue/green, or to the right – pink/red/yellow).

chains of domains. The vertical domain chain configuration (length and position of chains running from bottom to top in the Figure) is highly dependent on the presence of the horizontal domain chains (those running from left to right). Comparing our PEEM observations with micromagnetic simulations, we were then able to identify the key mechanisms responsible for the observed behaviour: 1) the ends of orthogonal chains prefer to coincide because they form a stable domain wall configuration and 2) as the linear chains grow, the moving chain end is blocked by a horizontal chain due to the formation of high angle domain walls.

The antidot arrays have allowed us to observe the details of nucleation, propagation and pinning of magnetic domains in a regular array of nanoscale defects. We found that the final colour design of this magnetic carpet is not only determined by the arrangement of the cavities, but also strongly depends on the pre-existing magnetic configuration, which is in turn dependent on the applied magnetic field history in terms of strength and orientation. The ability to trap the domain walls present at the ends of the domain chains via the existing magnetic structure is potentially interesting for engineering of new magnetic nanoscale devices which exploit domain walls to store information or perform logic operations [8].

The uncovering of the nature of nanoscale antidot arrays has only been possible due to the fruitful collaboration with D. Backes, S. Czekaj, L. Lopez-Diaz, M. Kläui, U. Rüdiger, C.A.F. Vaz, J. A. C. Bland, R. J. Matelon, U. G. Volkmann, P. Fischer and M. Horisberger. ■

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# Revisiting the thorium-uranium nuclear fuel cycle [DOI: 10.1051/EPN:2007007]

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**T**HE thorium-uranium nuclear fuel cycle, in which the main fissile nucleus is uranium 233 and fuel regeneration is ensured through neutron capture on thorium 232 offers many potential advantages as compared to the better known uranium-plutonium fuel cycle. These include, in particular, reduced high activity long lived waste production and less likelihood of nuclear proliferation. A brief description of the nuclear reactors being considered for this fuel cycle is given. We show also that a strategy can be put together to constitute the initial uranium 233 supply for such reactors, using today's pressurized water reactors and a thorium and plutonium mixed oxide fuel.

## Introduction

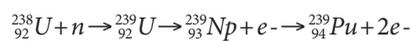
Today's reactors burn essentially uranium 235; they use only about 1% of the natural uranium [1]. For this reason, uranium reserves are estimated to provide about a century of reactor operation, the actual time span depending on the number of reactors in operation in the world and on the accepted cost of natural uranium. In the 1950's, because of these relatively small reserves, reactor physicists proposed to develop *breeder* reactors, in which the main fissile nucleus is no longer uranium 235 but either plutonium 239 or uranium 233 instead. Indeed, when these nuclei fission, they emit enough neutrons to ensure their replacement (breeding) through neutron capture on uranium 238 or thorium 232 respectively. Neither plutonium 239 nor uranium 233 can be found on earth in significant amounts so that they have to be produced if reactors using them are to be developed. Plutonium 239 is produced automatically in almost all of the reactors that are being operated worldwide, since these burn uranium-based fuels. The availability of large amounts of plutonium led to the development of the so-called uranium-plutonium fuel cycle, a concept that was realised in France with the Phenix and SuperPhenix breeder reactors. By contrast, the

amounts of uranium 233 available remained tiny, insufficient to allow the rapid development of a thorium-uranium concept.

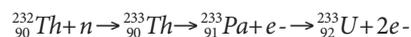
It appears today that the growth rate of nuclear power worldwide does not require the fast development of breeder reactor concepts. It is then possible, as we show in this paper, to constitute a stockpile of uranium 233 that could allow the development of a fleet of thorium-uranium reactors. We show also that such a concept has many major advantages, in particular concerning the disposal of radioactive waste and the risks of nuclear proliferation. We give a brief description of the types of reactors being considered to implement this fuel cycle and of a strategy that makes use of today's reactors to create the initial stockpiles of uranium 233.

## The advantages of the thorium fuel cycle

Breeder nuclear reactors such as SuperPhenix are based on the uranium 238-plutonium 239 fuel cycle. In this cycle, the plutonium, whose fission is the source of energy released in the reactor, is replaced by the new plutonium obtained through the capture of a neutron by a uranium 238 nucleus:



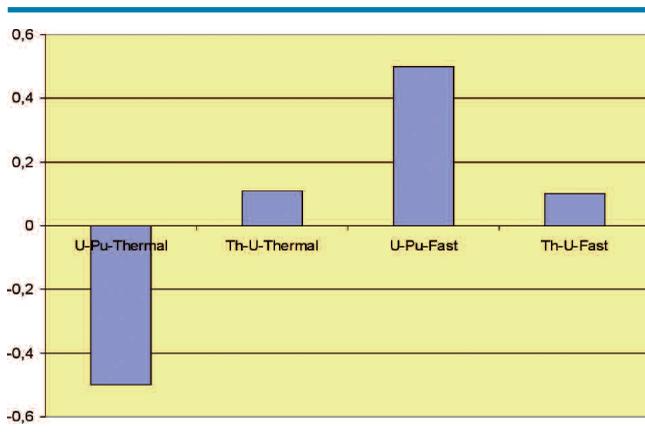
In the thorium 232-uranium 233 cycle, thorium 232 plays the role of uranium 238 and uranium 233 that of plutonium 239:



As Figure 1 illustrates, while the uranium 238-plutonium 239 fuel cycle requires fast neutrons to be sustainable, the thorium 232-uranium 233 fuel cycle is sustainable with either thermal neutrons or fast neutrons.

## A small initial inventory

The probability that the fission of a fissile nucleus ( ${}^{239}\text{Pu}$  or  ${}^{233}\text{U}$ ) will occur relative to the probability of a simple neutron capture on a fertile nucleus ( ${}^{238}\text{U}$  or  ${}^{232}\text{Th}$ ) is larger with slow neutrons than with fast neutrons. As a result the amount of fissile nuclei necessary for a reactor with slow neutrons to operate is usually smaller than that needed for a reactor with fast neutrons. Thus, in the case of the uranium 238-plutonium 239 cycle, the amount of  ${}^{239}\text{Pu}$  required to operate a fast neutron breeder reactor with a thermal power output of 3 GW is typically on the order of 7 to 14 metric tons [2] (depending on the amount of plutonium held up in the reprocessing system, the in-core inventory being on the order of 7 metric tons). In the case of the thorium 232-uranium 233 thermal cycle, the amount of  ${}^{233}\text{U}$  required to operate a slow neutron breeder reactor with the same power output is only 1.5 to 3 metric tons [3]. As a result, the production (by thorium 232 irradiation in a "classical" reactor) of the initial uranium 233 load for a thorium-uranium breeder reactor would be four times shorter than the production (by uranium 238 irradiation in the same type of reactor) of the initial plutonium 239 load for a uranium-plutonium breeder reactor.



▲ **Fig. 1:** Number <n> of neutrons available for breeding in the uranium-plutonium and the thorium-uranium cycles with thermal and fast neutron spectra. Breeding is impossible for negative values of <n>.

## Reduced Radioactive Wastes

After a few centuries, the radiotoxicity of radioactive wastes is due mainly to that of the heavy ( $Z > 92$ ) alpha emitting radioactive nuclei that are produced by successive neutron captures in the heavy elements present in the nuclear fuel. In breeder reactors based on the uranium-plutonium cycle, the uranium and plutonium are normally completely used up after fuel processing, they contribute very little (leakage during fuel processing) to the radiotoxicity of the wastes which is, because of this, two orders of magnitude smaller than in the case of classical PWR [4] reactors as illustrated in Figure 2.

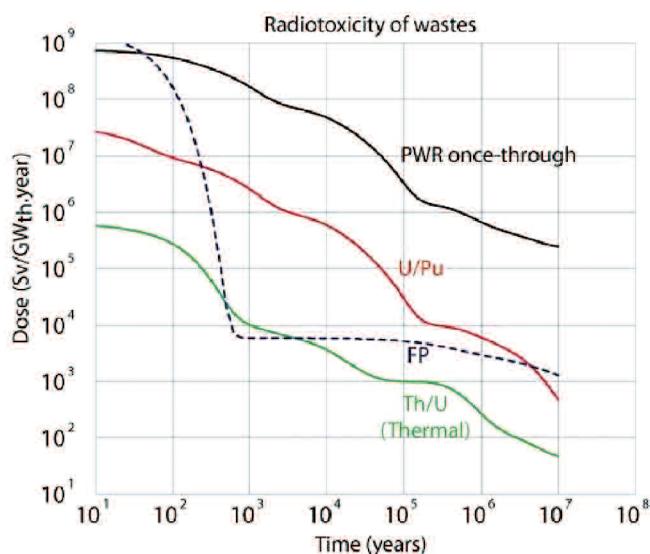
In other words, for an equal amount of energy produced, the geological storage needs will be nearly a hundredfold smaller with a uranium-plutonium based breeder reactor fleet than with the present day scheme. The thorium-uranium fuel cycle is even better than this perspective because, since the mass number of thorium 232 is 6 units less than that of uranium 238, the production of minor actinides (neptunium, americium, curium) which are the major contributors to the radiotoxicity of the wastes in the uranium-plutonium cycle is drastically reduced. Figure 2 shows that the radiotoxicity of the wastes in the thorium-uranium cycle is much smaller than that of the uranium-plutonium cycle during the first 10 000 years. It is noteworthy that the reduced initial radioactivity in this cycle would allow large savings on the size and, as a consequence, the cost, of geological storage [5].

## A Non-proliferating Fuel

An important condition for the manufacture of a nuclear weapon is that the fissile elements have low intensity gamma decay since the presence of high gamma activity would require very thick lead or lead-glass protections behind which operators would have to work. The uranium 235 obtained from isotopic separation plants has a low intensity gamma emission, just as the plutonium retrieved from reactor spent fuel. In general, the production of uranium 233 entails also the production of uranium 232 whose half life is 70 years. Successive alpha decays of uranium 232 lead to thallium 208 which decays with the emission of a very deeply penetrating 2.6 MeV gamma ray. It is thus practically impossible to manufacture a uranium 233 based weapon in the presence of uranium 232 contamination. True, this advantage regarding proliferation has its counterbalance in the more complex reactor fuel handling and manufacture. The entire process has to be automated or has to be executed behind heavy shielding.

## Large reserves

The thorium terrestrial reserves are estimated to be about four times those of uranium. Specifically, India, Brazil, Madagascar boast of large and very rich thorium beds. By contrast, thorium is not very soluble in water so that its extraction from sea water is not being considered, contrary to that of uranium. We should

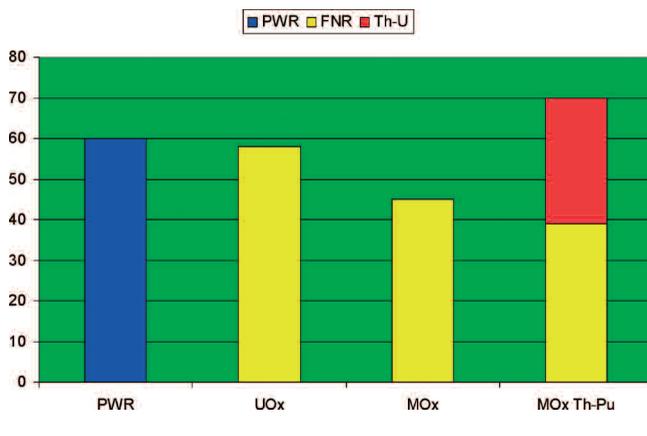


▲ Fig. 2: Time evolution of the radiotoxicity of high activity radioactive wastes per unit energy produced by the reactor (Thermal GigaWatts x year) for various fuel cycles. Nuclear wastes are due on the one hand to the actinides leaked during fuel processing (their amount depending on the type of reactor concerned) and on the other to the fission products (their amount depending only on the amount of energy produced). "At equilibrium" applies to closed cycle reactors (U/Pu and Th/U breeders; it means that the condition has been reached where equal amounts of minor actinides are created and destroyed in the reactor.

stress, however, that breeder reactor technology being very thrifty in its use of the fuel, even low content ore could be worked profitably, ensuring that fuel would remain available over several thousand years both for uranium and thorium based breeder reactors. The fact that thorium reserves are larger is thus not an important issue.

## What reactor types for the thorium fuel cycle?

With the thorium-uranium fuel cycle, breeding can be achieved with fast neutrons and also with slow neutrons. With fast neutrons, it is more tricky than with the uranium-plutonium fuel cycle: the initial uranium 233 inventory is large, on the order of 5 metric tons for a 3 GW thermal power reactor. This represents the in-core inventory, to which the uranium in the fuel reprocessing system should be added (uranium in the processing unit and uranium on standby pending reprocessing). It follows that the doubling time [6] becomes quite large. As a consequence, fast neutron thorium-uranium reactors will be iso-breeders in practice. They could be similar to the fast neutron reactors based on the uranium-plutonium fuel cycle, for example those with a molten metal (sodium or lead) coolant.



▲ **Fig. 3:** Number of breeder reactors that could be started after a fleet of 60 GWe PWRs have operated over 40 years. In blue, the number of PWRs. In yellow, the number of uranium-plutonium breeder reactors that could be started with the plutonium from a UOX fuel fleet without MOX, from a classical MOXed fuel fleet burning uranium-plutonium MOX, and from a thorium-uranium MOXed fleet. In red, the number of thorium-uranium breeder reactors that could be started from the uranium 233 produced in the latter case.

Thorium-uranium breeder reactors with slow neutrons need only a small uranium 233 inventory, on the order of 1 metric ton. Their theoretical doubling time is similar to that of uranium-plutonium fast neutron breeder reactors. However, fission products are much more efficient in poisoning slow neutron reactors than fast neutron reactors. Thus, to maintain a low doubling time, neutron capture in the fission products and other elements of the structure and coolant have to be minimized. An elegant theoretical solution to this problem was proposed in the 1960's, namely, a reactor in which the fuel is a molten salt which also serves as the coolant. Neutron capture on the fission products would be limited thanks to on-line salt recycling, at the cost of additional complexity since the reactor becomes also a chemistry factory. Giving up the low doubling time objective opens the way to molten salt reactors with drastically simplified on-line fuel processing or to other reactor types, such as those with in-operation fuel loading/unloading such as heavy water reactors (CANDU) or gas-cooled pebble-bed reactors. A particularly interesting scheme would consist in complementing a thorium-uranium reactor fleet with fast neutron reactors with a uranium-plutonium core surrounded with a thorium blanket that could produce the uranium 233 needed in excess to extend an existing thorium-based reactor fleet.

### Advantages and drawbacks of uranium-plutonium MOX fuels

Following the 1973 oil crisis, French experts had anticipated a rapid development of worldwide nuclear power production similar to the policy that France was about to implement. There would then be a risk that uranium resources, which are poorly utilized in PWR type reactors, would be insufficient. As a consequence, France, taking advantage of the experience acquired on the Rapsodie experimental reactor and the Phenix prototype reactor (first criticality 1967 and 1973 respectively), set out resolutely to develop sodium-cooled fast neutron breeder reactors (FNR) with the construction of Super-Phenix (initial decision in 1973, beginning of construction in 1976, first

criticality in 1985). In addition, the creation of a plutonium separation unit (La Hague) and of a plutonium loaded oxide fuel manufacturing unit was decided, these being necessary for the supply and manufacture of the breeder reactor cores.

The anticipation of the French experts did not come true, on the one hand because of the development of coal burning power plants, whose investment costs are less than those of nuclear power plants and on the other because of the Three Mile Island accident which put an end to the construction of nuclear power plants in the United States. Thus, the economic argument in favor of FNRs vanished. At the same time, their development was confronted with the virulent opposition of the anti-nuclear movement which saw them, and rightly so, as fulfilling the condition for sustainable nuclear power. The political decision that led to the shutdown of Super-Phenix, supported by the technical difficulties encountered during the first years of the reactor's operation [7], put an end to the FNR program in France at least in the short and medium term. In order to make the best of the considerable technological and financial investments as well as the human resources placed in the La Hague and Marcoule factories, the decision was made to burn the extracted plutonium in the PWR reactors. This is the MOX program in which the fuel is a mixed uranium and plutonium oxide whose composition is near stoichiometry:  $(U_{1-x}Pu_x)O_2$  with  $x=0.05$ .

There are undisputable advantages to the MOX program: less uranium 235 consumed, considerably smaller volume of the high-activity long-lived wastes and their conditioning in very stable glass matrices, maintenance of a technical and industrial know-how which is unique in the world and constitute an exceptional asset for France in the advent of renewed nuclear power development in the world.

But there are also drawbacks to the MOX program. Irradiated MOX fuels are set aside with the idea that the plutonium they still contain could be used in future reactors. But spent UOX [8] fuels contain more plutonium and of better quality before their reprocessing than the irradiated MOX fuel thus set aside. Burning MOX fuel, then, jeopardizes the ability to constitute the fuel stockpiles needed to deploy a fleet of FNRs in the future. In addition, irradiated MOX fuels are about 5 times more radioactive than irradiated UOX fuels, making their surface storage and, even more so, their permanent geological storage more difficult.

### Advantages of thorium-plutonium MOX

Today's MOX fuels are comprised of approximately 5% plutonium for 95% natural or depleted uranium. While the irradiation tends to decrease the initial amount of plutonium, the presence of uranium 238 leads to a partial reconstitution of the plutonium stockpile. The destruction of plutonium can be speeded up by replacing the uranium in the MOX with thorium, the result being thorium-plutonium MOX.

Today, a PWR burning uranium-plutonium MOX incinerates approximately 544 kg plutonium per year (for the simplicity of the argument, we assume here a "fully MOXed" PWR while, in fact, only one third of the fuel of a PWR is "MOXed"). A "fully MOXed" PWR loaded with thorium-uranium MOX should produce approximately 280 kg of uranium 233 per year while it incinerates approximately 800 kg of plutonium, producing about 20% less minor actinides. However, the quality of

the plutonium unloaded, as measured by the relative amount of fissionable plutonium isotopes, would be somewhat degraded. These results are summarized in Table 1.

Nucleus	At loading (Kg/8TWhe)	MOX Production (Kg/8TWhe)	Th Mox Production
$^{233}\text{U}$	0	0	278.72
$^{239}\text{Pu}$	1008	-500	-650
Total Pu	1900	-544	-800
M.A.	0	139	119

▲ **Table 1:** Comparison of the effect of MOX and thorium MOX fuels. The plutonium loaded comes from reprocessed UOX fuel and the small proportion of uranium 235 remaining in the uranium-thorium MOX is neglected. (Results from an "order of magnitude" simulation of a 1 GWe reactor operating 91% of the time).

The inventory of a fast neutron uranium-plutonium 1 GWe (electric GigaWatt) breeder reactor is approximately 7 to 14 metric tons. That of a slow neutron thorium-uranium 233 1 GWe breeder reactor would be approximately 1.5 metric tons. The plutonium incineration using uranium-plutonium MOX in a PWR would thus destroy 8% of the initial inventory of an FNR [9], while plutonium incineration with thorium-plutonium MOX in a PWR produces approximately 18% of the initial inventory of a thorium-uranium 233 [10] breeder reactor. The development of a breeder fleet, then, is not jeopardized if plutonium incineration is done with thorium-plutonium MOX. Moreover, since plutonium is no longer produced from the uranium, the net amount of plutonium incinerated would be increased by 150 kg. In Figure 3, these considerations are illustrated in the case of a PWR reactor fleet partly loaded with thorium MOX fuel (assuming that all the plutonium produced in UOX fuels is recycled in thorium MOX). In this hypothesis, the number of thorium-uranium breeder reactors obtained is significantly larger than the number of uranium-plutonium reactors "lost" because of plutonium incineration. As mentioned in the introduction, one of the reasons which disqualified thorium-uranium breeders as compared to uranium-plutonium breeders was, precisely, the non-existence of a uranium 233 stockpile to start with, while the PWR, BWR heavy water, and graphite moderated reactors were producing large amounts of plutonium. The advent of thorium-uranium MOX fuels would change the picture completely. Moreover, if, in the end, there were to be no breeder reactor program, the uranium 233 could be burned in standard reactors without entailing the production of large amounts of plutonium or minor actinides.

## Conclusion

It would be unfortunate if orientations were to be decided on the basis of fast decisions made without true scientific and technological debates concerning future reactors and fuel cycles, using the argument that different orientations would break away too radically from currently accepted procedures. There is no real hurry for the definition of the systems of the future and the times lend themselves to open and thorough reflection. Granting, however, that pencil and paper designs are not sufficient, small scale prototypes of the more promising reactors will have to be built within the frame of international collaborations.

It would thus be worthwhile to resume the molten salt reactor program that was started in the 1960s at the Oak Ridge National Laboratory in the US, with the construction of a reactor prototype with a power capacity of a few ten MW. Likewise, there seems to be no valid reason to prevent the in-reactor irradiation of a few thorium MOX fuel assemblies. Finally, France should try to initiate a collaboration with Canada and India with a view to evaluating the potential of CANDU reactors vis-à-vis the thorium-uranium 233 fuel cycle. ■

The original version of this article has been published in French in the *Bulletin de la Société Française de Physique*, **152**, 26 (2006).

## For further informations see:

- 1) H.Nifenecker, O.Méplán and S.David, *Accelerator Driven Subcritical Reactors*, IOP (2003) and references therein
- 2) Luc Mathieu, *et al.*, "The thorium molten salt reactor : Moving on from the MSBR", *Progress in Nuclear Energy* **48** (2006) 664-679
- 3) <http://lpsc.in2p3.fr/gpr/gpr/index.htm>

## Notes

- [1] Natural uranium contains 0.7% uranium 235 and 99.3% uranium 238. The fuel of French PWR reactors is uranium, slightly enriched to 3.5% in uranium 235. 60% of the fissions in the reactor are due to uranium 235 and the rest are due essentially, and indirectly, to uranium 238 via plutonium 239 resulting from neutron capture on uranium 238.
- [2] In a uranium-plutonium breeder reactor, the initial plutonium load amounts to 15 % to 18 % of the initial uranium load.
- [3] In a thermal thorium-uranium breeder reactor, the initial uranium 233 load amounts to 1.5 % of the initial thorium load.
- [4] PWR: Pressurized Water Reactors, the only reactors operated commercially in France and the most widespread worldwide. BWR: Boiling Water Reactors, the second most widespread reactors having similar fuel use properties.
- [5] Without taking into account the need to handle the stockpiles that exist today and those that will be produced by the next generation of European Pressurized Reactors (EPR).
- [6] The doubling time is the time needed to produce as much uranium (or plutonium respectively) as the initial amount needed, i.e. obtain the equivalent of two initial loads starting from one initial load.
- [7] See (in French) « Super-Phénix, pourquoi ? » by G. Vendryes, Ed. Nucléon (1997) and, on the site of the French Physics Society (SFP): [http://sfp.in2p3.fr/Debat/debat\\_energie/Nucleaire/Reacteurs/superphenix.html](http://sfp.in2p3.fr/Debat/debat_energie/Nucleaire/Reacteurs/superphenix.html)
- [8] The initial composition of UOX fuels is uranium oxide, UO<sub>2</sub> (with a c.f.c. structure of the CaF<sub>2</sub> type) where the uranium is slightly enriched. After irradiation, they contain the fission products, plutonium and minor actinides (neptunium, americium, curium). Reprocessing consist in extracting the plutonium and uranium and mixing the other elements in a glass matrix. As irradiation levels increase, the proportion of fissile isotopes in the plutonium decreases (especially plutonium 239) with a corresponding increase in the non-fissile isotopes of plutonium (especially plutonium 240). This constitutes an advantage vis a vis proliferation but a drawback for a reactor fuel.
- [9] Really, 544/7000 where 544 is obtained from Table 1.
- [10] Really, 278/1500 where 278 is obtained from Table 1.

# Towards nanospintronics [DOI: 10.1051/EPN:2007008]

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“WHEN we get to the very, very small world - say circuits of seven atoms - we have a lot of new things that would happen that represent completely new opportunities for design. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins...” suggested R.P. Feynman in a famous visionary talk in 1959. This statement forecasts the present development of two very active trends in solid state physics: molecular electronics and spin electronics (or spintronics). Molecular electronics involve charge transport through the quantized energy levels of a molecule, whose spectrum is possibly controlled by an external voltage. Spintronics involve the control of electronic transport through the spin degree of freedom [see *e.g.* the article by A. Fert et al. in the special issue on Magnetism, *EPN* 34, N°6 (2003)]. Although these fields had developed independently so far, some researchers have started to combine them. Nano-spintronics investigates the interplay between quantum transport through molecules or nanoparticles and spin-dependent phenomena induced, for example, by magnetic electrodes. Beyond the fundamental purpose of investigating the physics of low-dimensional electronic systems, this topic of research could have many potential applications in the future. For instance, it could lead to the implementation of the counterpart of the field-effect transistor (FET), namely the spin-FET, in which spin transport would be controlled through an electrostatic gate. Nanospintronics could also be useful for building spin-based quantum bits, *i.e.* devices in which single spins would be used to encode quantum information. In this context, one can imagine to manipulate quantum information by using gate-controlled effective magnetic fields.

## Electrical polarizer/analyzer experiments

Electronic spin has emerged as a primary tool to control current transport in electronic devices. One basic building block of spintronics is the spin-valve. This element consists of two ferromagnetic electrodes contacted through a “spacer” such as a thin insulating barrier or a non-magnetic metal (Fig.1, left). Electrons can pass through the insulating barrier by quantum mechanical tunneling or can freely propagate through the non-magnetic metal. The spin-valve effect is based on the existence of spin-dependent densities of states in the two ferromagnetic electrodes. In a simplified description, the state of a ferromagnetic metal can be described with a polarization vector  $\vec{P}$ . The metal contains electrons with two opposite spin directions, one majority direction parallel to  $\vec{P}$ , with a density of states  $N_M$ , and one minority direction parallel to  $-\vec{P}$ , with a density of states  $N_m$ , such that  $|\vec{P}| = (N_M - N_m) / (N_M + N_m) \neq 0$ . A spin polarization  $|\vec{P}| = 100\%$  means that only one spin species can propagate through the metal. Let us assume that the spin valve can be either in a parallel or in an antiparallel configuration, *i.e.* the polarization of the two ferromagnetic electrodes can be either parallel or antiparallel. If the transmission probability of the

electrons through the spacer is energy and spin independent, the resistance of the spin-valve is simply determined by this configuration. In the extreme case of fully polarized ferromagnets ( $|\vec{P}| = 100\%$ ), the situation is analogous to a polarizer/analyzer experiment in optics (Fig.1, right). The majority and minority spin directions correspond to the two polarizations of light. In the parallel configuration, the “polarizer” and the “analyzer” are matched, thus spins incident from one electrode are allowed to propagate to the other. In the antiparallel configuration, the “polarizer” and the “analyzer” are crossed. Therefore, a spin from one electrode cannot propagate to the other electrode, and no current can flow through the device. The spin valve thus acts as a switch (or a valve) which can be turned on or off simply by changing the configuration of the ferromagnets. In practical devices, the spin polarization is not 100% and minority carriers can conduct, but the spin valve resistance is larger in the antiparallel configuration. Since the configuration of the ferromagnets can be controlled by applying an external magnetic field, spin valves can be operated as particularly sensitive local magnetic sensors. This phenomenon, discovered about 20 years ago [1,2], is the basic principle nowadays of hard-disk read-out in computers.

## Spin Field Effect transistors using molecules ?

An increase of resistance upon switching from the parallel to the antiparallel configurations is expected for conventional spin-valves. Nevertheless, when the transmission probability through the spin valve spacer is either energy or spin dependent, the resistance change upon switching between the parallel to the antiparallel orientation is not necessarily positive. The possibility of controlling the magnitude and the sign of this quantity, called the *magnetoresistance*, would allow new spintronics devices to be built. This task requires that appropriate spacers be found which can allow such a control. Molecules are ideal candidates to implement this new functionality because they can be coupled to ferromagnetic electrodes and they allow a good coupling between electronic transport and local electric fields.

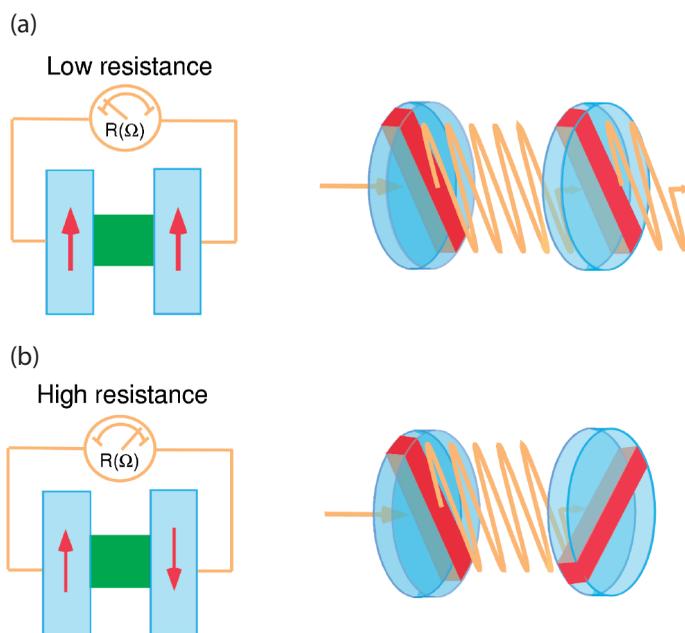
The analogy with polarizer/analyzer experiments turns out to be illuminating in this situation also. Indeed, it has been used to describe the basic principle of one of the most famous proposals of a spintronic device suggested in 1990 by S. Datta and B. Das [3]. The electro-optic modulator is a widely used analogue in which an incoming linearly polarized beam propagates through a birefringent medium. The rotation of the beam polarization is controlled by applying to the medium an electric field which changes the refractive index of the medium in a specific direction. The polarization of the beam is subsequently analyzed. For electrons, an analogue of the birefringent medium is a ballistic single mode conductor with an electrically tunable spin-orbit coupling (Rashba effect). The spin-orbit coupling induces a magnetic field in the

moving frame of the electrons, which causes spin precession. If the Rashba field is low, little spin precession occurs between the two ferromagnetic electrodes. The device thus acts as a regular spin-valve with a positive magnetoresistance. If the field is such that each spin precesses by  $\pi$  upon travelling through the ballistic region, the magnetoresistance of the device becomes negative. Two dimensional electron gases (2DEGs), which can be realized in semiconductor heterostructures, have been primarily envisioned for the implementation of the Datta-Das transistor. However, the electrical injection of spins in 2DEGs has turned out to be very difficult to achieve. To date, such a device has not been realized experimentally.

Very recently, carbon nanotubes have emerged as an alternative to semiconductor heterostructures for the implementation of spin logic devices [4,5]. Two different types of carbon nanotubes can be fabricated: single-wall nanotubes (SWNTs) and multi-wall nanotubes (MWNTs). A SWNT consists of a single graphene sheet that is rolled up into a cylinder. A MWNT consists of a set of coaxially stacked graphene cylinders. A spin-valve can be formed by evaporating two separate ferromagnetic contacts on a nanotube lying on an highly doped silicon substrate. The silicon substrate can be used as a capacitive gate for the nanotube because its surface is oxidized. At low temperatures, quantum interferences occurring in the nanotube (just as for particles in a box) select the energy of electrons crossing the spin-valve. In situations where electronic interactions effects can be neglected inside the nanotube, one can push further the analogy with optics since the carbon nanotube then behaves like a Fabry-Perot electronic interferometer [6]. Due to multiple coherent reflections in the “Fabry-Perot cavity”, the magnetoresistance of the spin-valve does not depend only on the configuration of the ferromagnets, but also on whether constructive interferences take place in the interferometer (Fig.2). Provided that the transmission from the nanotube to the two ferromagnets is very asymmetric, the magnetoresistance of the spin valve is negative if the nanotube is on resonance. If it is off resonance, the picture of the conventional spin valve is recovered, and the magnetoresistance is positive. The on/off resonance regimes can be tuned by varying the gate voltage of the nanotube since this modifies the wavelength, hence the “optical path” of the electronic waves. This allows the magnetoresistance of the device to be changed in a controlled way, as found experimentally for SWNTs connected to ferromagnetic contacts [4,5].

The Spin-FET principle described above is very general. In principle, any kind of molecule can be used to implement such a device. In cases where electronic interactions are significant, in the molecule, the description of electronic transport becomes more complicated. The molecule can, for instance, behave as a quantum dot which is characterized by at least two energy scales. The first one is the intrinsic level spacing arising from size quantization of the electronic orbitals, already

present in the Fabry-Perot case. The second one is the charging energy characterizing the Coulomb blockade effect caused by the very small capacitance (a few aF) of the tunnel junctions used to contact the molecule. Nevertheless, the features recently observed [4] in such a case can be qualitatively understood in terms of polarizer/analyzer experiments with a Fabry-Perot interferometer. One practical difference between optics and spin electronics is that it is difficult to find ferromagnetic materials with a spin polarization close to 100%. This is *a priori* even more difficult for materials which can be coupled to molecules. However, this is essential to obtain efficient Spin FETs, that is devices transforming spin information into sizable electric signals. This important step towards spin logic devices has been made very recently by using the highly spin-polarized manganite  $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$  (LSMO) to contact carbon nanotubes [7].



▲ **Fig. 1:** a) Schematic diagram of a spin valve in the parallel configuration (left) and its optical analogue (right). The spin-valve consists of two ferromagnetic electrodes (blue blocks) electrically connected through a “spacer” such as a tunnel barrier or a non-magnetic metal (green block). The magnetic polarization  $\vec{P}$  of each ferromagnetic electrode is represented as a red arrow which indicates the direction of majority spins. It is the analogue of the polarization axis (red line) of each optical polarizer (blue disk) in the right scheme. In the parallel configuration, the resistance of a conventional spin valve is low. This corresponds to having aligned polarizers and a maximal transmission of photons in the optical scheme. b) Schematic diagram of a spin valve in the antiparallel configuration (left) and its optical analogue (right). The resistance in this configuration is high for conventional spin valves.

## Towards the manipulation of a single electronic spin

The spin-FET described above allows a gate control of spin-transport in the statistical sense, that is for an average current corresponding to a large number of electrons. In the context of quantum information processing, it would be very interesting to achieve a further control of the spin degree of freedom, *i.e.* to find ways to control directly a *single* electronic spin using a gate electrode. Electron-electron interactions are recognized as a very important ingredient to manipulate the spin in confined conductors. The Coulomb blockade effect already evoked above tends to force the occupation of the conductor by a single spin. This is the basic principle of spin-based quantum bits [8]. In multiple quantum-bit devices, the selective control of the spin-precession of a single spin would require one to apply a tunable local magnetic field to each spin. The presence of ferromagnetic contacts can induce various types of local effective magnetic fields in molecules, which could be very useful in this context.

Polarization-dependent phase shifts are well known in optical fibre physics. They arise for example from the induced birefringence of an optical fibre under stress. These effects usually lead to inaccuracies in interferometric measurements because they change the optical path for two different polarizations [9]. The spintronics counterpart of this effect is the so-called Spin Dependence of Interfacial Phase Shifts (SDIPS), which affects, via the spin, the phase of the electronic wave functions. In a cavity, the SDIPS generates an effective field which depends of the “optical path” [10]. The latter is controlled, in the case of molecular spin-valves, by the gate electrode. The presence of electronic interactions in the molecule can lead to additional gate-tunable effects other than that arising from the SDIPS. An effective field of 70T

measured in  $C_{60}$  molecules coupled to ferromagnetic electrodes has been attributed to Coulomb interaction effects [11]. One could imagine using these effective fields to perform single spin operations in the context of quantum information applications. ■

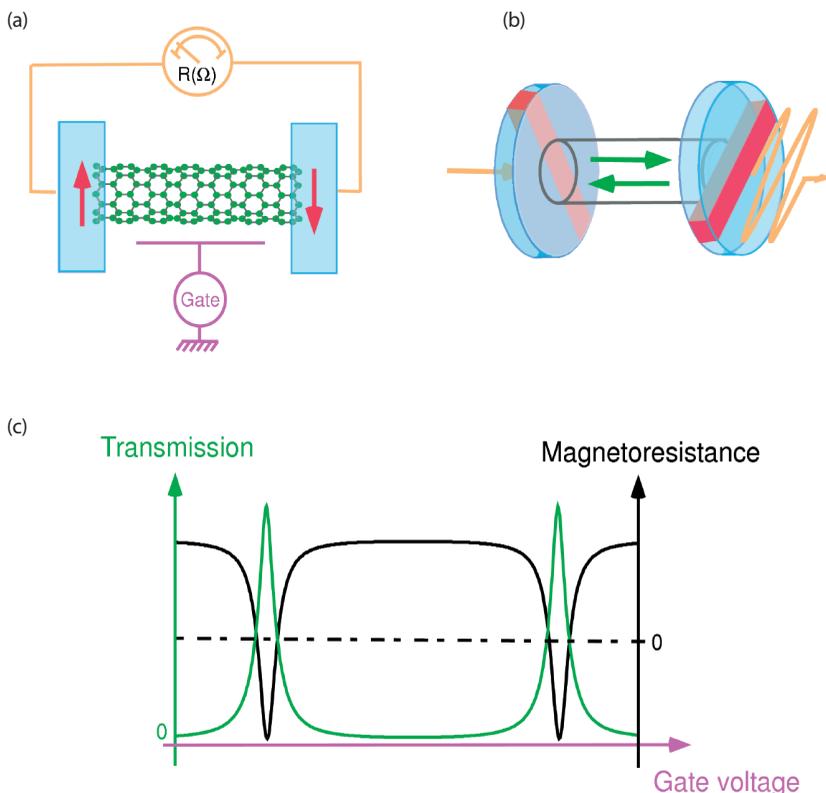
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◀ **Fig. 2:** a) Schematic diagram of a Spin Field Effect Transistor made out of a Single Wall Carbon Nanotube contacted to two ferromagnetic electrodes and capacitively connected to a gate voltage source. We assume that the couplings between the nanotube and the two ferromagnets are very asymmetric. We present here the case of an antiparallel configuration for the ferromagnetic contacts. Assuming that the gate voltage is such that the interferences occurring inside the nanotube are constructive, the resistance of the transistor is lower in this configuration than in the parallel configuration. This leads to a negative magnetoresistance. b) Fabry-Perot interferometer inserted between a polarizer and an analyzer. This device would be the optical counterpart of the circuit of panel a). c) Typical transmission and magnetoresistance as a function of the gate voltage, for the spin-transistor of panel a). The magnetoresistance becomes negative when the transmission of the transistor is resonant.

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